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Flight Display Integration

Guy A. French
Darrel G. Hopper
John M. Reising

Human Effectiveness Directorate
Warfighter Interface Division
Wright-Patterson AFB OH 45433-7022

Michael P. Snow

The Boeing Company
P.O. Box 3707 MC 0R-HK
Seattle WA 98124-2207

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Final Report for October 1999 to October 2006

Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
System Control Interfaces Branch
Wright Patterson AFB OH 45433

NOTICE

TECHNICAL REVIEW AND APPROVAL

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THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

FOR THE DIRECTOR

//signed//

DANIEL G. GODDARD
Chief, Warfighter Interface Division
Air Force Research Laboratory

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This report begins with a discussion of the analysis of the human and display factors relevant to synthetic vision in a military cockpit environment. It then describes the results of studies examining the impact of synthetic vision displays on pilot situation awareness and workload. Concluding remarks on additional factors affecting the use of synthetic vision and a future concept for its implementation are described.

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PREFACE

This final report describes activities performed in support of the Air Force Research Laboratory System Control Interfaces Branch (AFRL/HECI) under workunit #71840903. The work was accomplished during the period of October, 1999 through August, 2006 although the workunit was zero-funded in the years FY2004-2006. This report officially completes the workunit and discusses the general program background and significant technical accomplishments. Due to the loss of funding in FY2004, there was no additional technical work accomplished after that time. Thus, the bulk of the material contained herein has been extracted from interim reports published previously.

An FDI research group (consisting of AFRL/HECI, General Dynamics Advanced Information Engineering Services, and L3 Communications) provided human factors and software experts for the project. Their responsibilities are listed below.

US Air Force Research Laboratory (AFRL/HECI, WPAFB OH):

Antonio Ayala	Computer Engineer: Simulation Software
Guy French, Ph.D.	Engineering Psychologist: Experimental Design Data Collection, Data Analysis
John Reising, Ph.D.	Senior Crew Systems Research Engineer: System/Display Format Design
Michael Snow, Ph.D.	Crew Systems Research Engineer: System/Display Format Design

General Dynamics Advanced Information Engineering Services (Dayton OH):

Noel Cox	Senior Systems Engineer: Software Design, Data Collection
Joe Ferraro	Senior Systems Engineer: Software Design
David Murphy	Human Factors Engineer: Data Collection, Training
Tony Orr	Senior Operations Analyst: System Design, Subject Matter Expert
Mark Squire	Systems Engineer: Simulation Software, Data Collection

L3 Communications (Dayton OH):

Sam Longo	Senior Simulation Systems Engineer: Hardware Design
Thomas Whitman	Senior Software Engineer: Simulation Software

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INTRODUCTION

Data from the Air Force Safety Center show that, from 1990 through 2000, the Air Force lost 131 personnel and $1.44 billion in 63 mishaps falling into the category of Controlled Flight Into Terrain (CFIT). A CFIT mishap is one in which aircrew fly a serviceable aircraft into terrain due to inadequate prior awareness of impending disaster. Commercial aviation has a similar problem, suffering approximately four CFIT mishaps per year in Western transports from 1990 to 2000 (Phillips, 2001) with accompanying financial and human costs. Historically, technological approaches to preventing CFIT mishaps have focused on warning and automatic avoidance systems (e.g., the Ground Proximity Warning System). Such systems have been somewhat successful in treating symptoms of the CFIT disease – the imminent impact with terrain brought about by aircrew loss of situation awareness. However, their lack of complete success in preventing these mishaps may be at least partially attributed to the fact that they have not eliminated CFIT's root cause: that aircrew lose fundamental awareness of the relationship between the aircraft's flight path and surrounding terrain in the first place. The advent of newer CFIT-prevention systems (such as the Enhanced Ground Proximity Warning System) will improve terrain awareness, but will still require pilots to divert attention away from primary flight instruments and the out-the-window scene and still rely at least partially on alerts and warnings to avoid CFIT.

Several research and development efforts are now being conducted worldwide by institutions, civil and military, to prevent this critical loss of situation awareness by incorporating a concept known as synthetic vision in the cockpit. Synthetic vision refers to the portrayal of information in a database, usually in perspective view and usually as part of a primary flight display. This information can be based on an on-board database (e.g., digital terrain elevation data, airport and runway data) and can also include elements of off-board data (e.g., datalinked traffic information or assigned approach path). The goal of a synthetic vision display is to increase aircrew situation awareness by allowing a view of surrounding terrain, commanded flight path, air traffic, obstacles, or any other task-relevant information that is available and can be incorporated into the underlying database. Fundamentally, it is believed that if pilots can accurately perceive the surrounding terrain via a synthetic vision display, it will greatly reduce the likelihood that they will fly into it – or get into a situation that requires an alert or warning to avoid doing so. Further, the inclusion of commanded flight paths in these displays is designed to enable pilots to fly more complex paths with tighter tolerances under IFR (Instrument Flight Rules), allowing greater airport throughput and better avoidance of noise abatement areas.

Because synthetic vision displays are only as good as the databases and information that serve as their foundation, military concepts for this technology call for the integration of synthetic vision with sensor information and images. The two technologies are complementary in many ways. Whether or not integration of sensor images in civilian synthetic vision displays will prove practical and cost effective remains to be seen. There are several key technologies that enable synthetic vision displays, all maturing in the next few years.

This report begins with a discussion of the analysis of the human and display factors relevant to synthetic vision in a military cockpit environment. It then describes the results of studies examining the impact of synthetic vision displays on pilot situation awareness and workload. Concluding remarks on additional factors affecting the use of synthetic vision and a future concept for its implementation are described.

I. HUMAN FACTORS IN SYNTHETIC VISION DISPLAYS

Enabling technologies needed to provide pilots a synthetic view of the outside world are expected to mature within the next three to five years. Such a synthetic view, a display based at least partially on a database, is expected to greatly increase aircrew situation awareness in reduced visibility conditions with a consequent improvement in air safety. In particular, it is hoped that providing a synthetic view of the commanded flight path and the terrain surrounding the flight path will greatly reduce the incidence of controlled flight into terrain accidents. If a synthetic view can be provided to the pilot as part of his/her head-up primary flight display, the potential exists to provide these benefits while allowing the pilot's head, eyes, and attention to remain focused outside the cockpit.

This section reviews the current status of enabling technologies for head-up synthetic vision displays. Human factors issues associated with the design and display of information are discussed in detail. Among these issues are pilot information requirements, depth and self-motion cues provided, visual clutter in the head-up display (HUD), format of the synthetic view underlying other HUD symbology, integration with head-down displays, integration of the synthetic view with sensor information, and attentional issues. Examples of how these issues are considered in the design of a synthetic vision HUD are given, and recommendations made for the design of these displays based on this discussion and findings from human factors studies conducted by AFRL.

ENABLING TECHNOLOGIES

Precision Navigation Systems

In order to utilize any navigation system, knowing one's current position is highly desirable. To make the best use of an on-board terrain database for navigation, especially if trying to land in Instrument Meteorological Conditions (IMC), one needs to know one's position with great accuracy. To achieve acceptance from the aviation community, terrain databases need to be supported by a highly accurate system for precision navigation. Prior to the Global Positioning System (GPS), the ability to know one's own location was constrained by the available technology, based mostly on various radio beacons. Aviation regulations governing terminal operations and instrument flight were drafted accordingly. However, GPS promises to provide much greater accuracy and, as a result, current regulations will become needlessly conservative.

The National Air Space (NAS) system is receiving a major overhaul in order to incorporate GPS technologies. This overhaul will allow more precise navigation for all aircraft equipped with GPS. In simple terms, the NAS will rely on two different, but related, systems for accurate positioning of air vehicles: WAAS and LAAS. The Wide Area Augmentation System (WAAS) will consist of roughly 25 ground reference stations that will assess basic GPS data for errors, a ground master station that will calculate corrections for any detected errors, and a set of satellites that will broadcast the corrections to GPS equipped air vehicles. WAAS is expected to improve basic GPS accuracy from 100 meters to about 7 meters. The Local Area Augmentation System (LAAS) has a similar configuration to that of the WAAS in that it broadcasts a correction to the GPS data, further improving accuracy to approximately 1 meter in equipped areas. WAAS is expected to provide accurate data for enroute navigation, non-precision approaches, and ILS Category I approaches at some locations (http://gps.faa.gov/Programs/WAAS/waas.htm), while

LAAS will eventually provide the accuracy, availability, and system integrity required for ILS Category III approaches (http://gps.faa.gov/Programs/LAAS/laas.htm).

Being developed in parallel is a military system compatible with WAAS and LAAS: the Joint Precision Landing System (JPALS). JPALS is designed to supplement the WAAS and LAAS components for military air vehicles when operating in areas where there is no WAAS/LAAS infrastructure (e.g., OCONUS, austere landing fields, and at sea). Expected accuracy is approximately two meters, allowing approaches down to ILS Category II. JPALS will also incorporate anti-jamming features and rapid set-up time for the tactical version. Additionally, a U.S. Navy version of JPALS known as Shipboard Relative GPS (SRGPS) will increase accuracy to less than 1 meter and allow automatic carrier landings (McCarthy & Colby, 2000).

Avionics

Another technology necessary for synthetic vision to be useful is a display capable of showing the terrain image. Current CRT and LCD technologies are certainly capable of displaying synthetic imagery head-down. However, it is expected that incorporating the imagery in a conformal primary flight display (so that elements in the synthetic image directly overlay elements in the real world) will yield the greatest benefit (Wickens & Long, 1995). To show conformal synthetic terrain will require some form of head-up display (HUD), either a conventional HUD or a head-mounted display (HMD). Both of these technologies have limitations. Current conventional HUDs tend to have narrow fields of view, limiting the amount of the synthetic scene viewable by the pilot at any given moment. They are also limited in field of regard, allowing the scene to be viewable only from the HUD design eyepoint (or eyebox) on aircraft boresight. HMDs have the potential for much greater fields of view, allowing more of the scene to be viewed, and fields of regard limited only by the biomechanics of the human head and neck, allowing the scene to be displayed off-boresight as well. Current limiting factors of HMDs are optics weight and bulk, and head-tracking: the displayed image must be able to keep up with the motion of the head, especially if the real world is even partly visible. Misregistration in overlaid symbology, already an issue in a HUD fixed to the aircraft, becomes even more of an issue for an HMD that is not fixed in space, but is free to move – not only with intentional pilot head movements, but also as a result of helmet slippage and compression during high-G maneuvers. Display factors will be discussed in more detail in the next Section.

Databases

What shows up in the head-up display can be legible and updated as rapidly as the head can be moved, but if the underlying terrain database is not accurate, the imagery displayed still won't be entirely conformal to the real world, leading to potentially dangerous mismatches. The terrain in the database must be accurate and of sufficient resolution to allow all terrain flight hazards to be displayed in real-time. The Shuttle Radar Topography Mission collected data in an effort to improve the accuracy, resolution, and coverage of the terrain database for NIMA and the civil aviation community. The updated terrain database provides a resolution of approximately 30 meters with $\leq$ 16 m absolute vertical height accuracy, $\leq$ 10 m relative vertical height accuracy and $\leq$ 20 m absolute horizontal circular accuracy, between 60N and 56S (http://www.jpl.nasa.gov/srtm/statistics.html). Of even more concern than accuracy of terrain elevations is the accuracy of other elements included in the synthetic vision display, especially obstacles. Maintaining an accurate database that includes manmade changes in the aviation environment (e.g., towers, runway alterations, changes in controlled and restricted airspace) is a key challenge facing implementation of synthetic vision systems.

Symbology

The last key piece of a head-up synthetic vision system is the symbology displayed to the pilot. Regardless of other enabling technologies in the cockpit, what pilots actually see in head-up synthetic vision displays will be the final determinant of how useful these displays are, the situation awareness they afford to pilots, the workload they impose, and – ultimately – how safely aircraft with these systems will be piloted. This symbology has been a primary focus of work conducted in our lab and others in recent years.

HUMAN FACTORS ISSUES

There is a wealth of human factors issues associated with the use of synthetic vision in cockpits, whether one is designing for a head-down display or a head-up display. However, the fact that HUDs are monochrome and meant to be seen through makes them an especially challenging display for which to design synthetic vision symbology. Three general considerations that human factors engineers must take into account when designing these displays are, 1) the information requirements of the pilot, 2) depth and self-motion cues provided by the symbology, and 3) display principles appropriate to the hardware available.

Information Requirements

Most synthetic vision displays currently under research and development include more than just a view of synthetic terrain. To minimize attention management requirements (and associated workload), designers usually combine synthetic vision with a display to which the pilot might otherwise have to shift attention. One common example of this is including primary flight information in a synthetic vision display. This primary flight information often incorporates a perspective view of the commanded flight path; the technologies enabling synthetic vision also enable such tunnel- and highway-in-the-sky displays. Other examples of information included in synthetic vision displays include traffic, weather, and restricted airspace: currently all shown on cockpit displays that require division of attention between the primary flight display and the view out the window.

Information required by the pilot, and therefore considered for inclusion in a synthetic vision display, depends on the pilot's task at hand. A pathway-in-the-sky that might be useful when flying a complex, precision LAAS approach could also be one of the first things a pilot might declutter from the HUD when cruising at altitude. The information requirements also depend greatly on the role and mission of the aircraft.

One key difference in these roles and missions is whether the aircraft and crew are civilian or military. With regard to primary flight information, the requirements and standards for civil aviation (FAR 25.1303, Federal Aviation Administration, 2000) and military aviation (MIL-STD 1787C, U.S. Department of Defense, 2000) are essentially the same. However, sensors are more prevalent in the military aviation community than in the civil aviation community. A display of synthetic imagery designed for military use must be able to incorporate sensor imagery and, as sensor technologies become more cost effective, synthetic vision formats for civil aviation should also have this capability. The integration of imagery based on sensors with imagery based on a database has implications for the human factors engineering of these displays, driven by the relative strengths and weakness of each technology. Therefore, a synthetic vision display incorporating sensor imagery should allow the pilot to:

1. Display sensor imagery, synthetic imagery, both combined, or neither at his/her discretion.
2. Immediately and clearly discern the source of information in the image (sensor or database).

A synthetic image is only as good as the database and navigation system that serves as its source; similarly, a sensor image is only as good as the sensor and the environmental conditions in which it is operating. Meteorological conditions, phase of flight, and type of terrain can all affect the relative usefulness of each image and image source. The format of the synthetic vision display and the interface used to control it should support pilot decision-making with regard to which image, if any, to display.

To successfully meet the needs of aircrew, the synthetic vision display should not simply display data: it should display information. One example of the difference between these two is the format chosen for synthetic terrain. Rather than simply portraying a terrain database (even one with a photorealistic overlay), the synthetic vision display should attempt to portray what the aircrew needs to know about that data: the height of terrain relative to the aircraft, the location of obstacles that may be of concern, and the relationship between surrounding terrain and the aircraft's commanded flight path.

One key concern related to pilot information requirements is the possibility of attentional tunneling or cognitive capture: the idea that a synthetic vision display, especially one including a pathway or tunnel, will be so compelling and contain so much of the pilot's information requirements that awareness of other displays and events will deteriorate in comparison. There is much research still to be done in this area. Some authors report no difference in situation awareness on-path versus off-path (Snow & Reising, 1999), while others report a decrease in awareness of events and information not contained in the synthetic vision display (Olmos, Liang, & Wickens, 1997; Williams, 2000). To date, most of these studies have been done with HDDs and the differences found (or not found) seem to be highly task-dependent. It remains to be seen whether using HUDs for synthetic vision, and presumably focusing pilots' attention head-up rather than head-down will alleviate these concerns.

Depth And Self-Motion Cues

One concept of synthetic vision is that texture-mapping, satellite imagery, and terrain databases should be used to create a display that mimics daytime flight in Visual Meteorological Conditions (VMC). While such a display is certainly useful, there have been instances of CFIT in VMC, and even daytime VMC. Pilots flying over open water, desert, or snow often lack the normally rich visual cues that humans use to accurately perceive depth and self-motion. Knowledge of these cues allows human factors engineers to create synthetic vision display formats that, in many cases, allow pilots to better perceive depth and self-motion than if they were looking out the window in daytime VMC conditions. A brief description of some of the depth and self-motion cues that may be usefully incorporated into a head-up synthetic vision display follows.

<u>Perspective or splay</u> - Perspective refers to the angle of lines parallel to the observer's viewpoint. A common example of this used in introductory perception texts is the observer standing in the middle of a railroad track. The closer the observer is to the ground the greater will be the angle formed by the two rails. Perspective has been shown to be a critical cue in perception of altitude

by pilots (Flach, Warren, Garness, Kelly, & Stanard, 1997). Indeed, student pilots are sometimes told upon landing to look at a distant point down the runway to gauge height above it.

Depression angle – Depression angle is the perceived distance between lines perpendicular to the observer's viewpoint. Lines closer to the horizon are closer together.

Ground intercepts – Several authors have proposed displaying ground intercepts or drop lines between airborne objects and their two-dimensional location on the ground, both in static and dynamic displays. This seems especially helpful in judging relative distances or depth (Hendrix & Barfield, 1995).

Apparent size – When objects of a known or expected size (e.g., aircraft, path blocks) are presented, larger objects will be perceived as closer. The object must be something with which the observer is familiar, especially in terms of its size. As an example, the perceived distance to a runway shown in a synthetic vision HUD will be based on the pilot's familiarity with how big runways appear at certain distances.

Object interposition – In the natural world, it is a perceptual constant that an object closer to an observer will appear in front of any object behind it.

Motion parallax – Another perceptual constant in the natural world is that objects closer to an observer will show greater apparent motion relative to objects farther away. A relevant example of a display in which this is a particularly strong cue is that of a pathway-in-the-sky superimposed on a synthetic terrain grid. Lines perpendicular to the pilot's viewpoint in the pathway move more quickly in the pilot's field of view than corresponding lines in the underlying synthetic terrain grid.

Optical flow – Optical flow refers to the pattern and direction of movement of elements in the visual field. Optical flow slowly expanding from the center of the observer's field of view indicates slow movement directly ahead. Rapid optical flow from left to right with no expansion would imply that the observer is stationary, but pivoting to the left. Optical flow rate has been found to be a key determinant of perceived self-motion or egospeed (Dyre, 1997).

Discontinuity rate – Discontinuity rate refers to the rate at which edges (or texture elements) in the visual field pass a fixed reference point (e.g., the boundary of a HUD field of view). Given a texture or grid of fixed size, discontinuity rate will be directly related to how fast the observer is moving and can be key to accurate perception of egospeed (Ballard, Roach, & Dyre, 1998).

Relative height – Everything else being equal, objects higher in the observer's field of view (closer to the horizon) appear farther away than objects lower in the observer's field of view.

Texture gradient – When a texture is present, as in many synthetic vision portrayals, texture elements will appear larger at shorter distances and smaller at farther distances. The usefulness of this cue depends greatly on the texture (especially the granularity or size of texture elements) and the distance from the observer to the texture. Given enough distance (or altitude), this cue to depth and distance becomes useless as texture elements blend into obscurity (Surdick, Davis, King, & Hodges, 1997).

Relative brightness – Objects in the observer's field of view that are brighter tend to appear closer. In a monochrome raster-capable HUD, making nearer objects (such as a pathway) brighter than more distant objects (such as synthetic terrain) will reinforce correct perception of their relative distances.

Display Principles

There are many, many display principles that have emerged from human factors research over the years. Not all apply to HUDs or synthetic vision displays; some apply to these displays uniquely. Those that are (in the authors' view) most relevant are outlined below.

Minimize clutter – The primary reason that HUDs exist is to allow pilots to simultaneously attend to information displayed in the HUD and events in the external visual scene. To the extent that one allows HUD symbology to obscure the external visual scene, one might as well put the same symbology head-down, save the weight and cost of a HUD, and take advantage of the color capabilities of most HDDs. Every single symbol element in a HUD should be subjected to the question: "Does the pilot need to see this if it means blocking the view through the window?" If the answer is no, the symbol element should probably be declutterable and consideration should be given to discarding it entirely. Performance suffers when task-irrelevant clutter is displayed in a HUD (Ververs & Wickens, 1998).

It should be noted that minimizing clutter is not simply equivalent to reducing the number of pixels in the pilot's field of view at any given moment. Consideration must be given to the shape and content of what is displayed. The literature on visual search and visual perception leads us to conclude that some symbology elements will be more confusable than others (Wickens, 1992). Even though there may be relatively few symbol elements in the display, pilots will likely describe it as cluttered or "busy" if elements are easily confused because of their shape, size, position, or movement.

Conformality – One display principle unique to HUDs is that of conformality: to the extent possible, symbol elements in the HUD should be conformal, or analogous, to elements in the external visual scene. Examples of conformal symbology include the artificial horizon, flight path marker, and runway outline. A growing body of research indicates that the more conformal a symbology set is, the better pilots will be at simultaneously attending to the HUD symbols and to events in the external visual scene, especially if those events are unexpected (Foyle, McCann, Stanford, & Schwirzke, 1993; Martin-Emerson & Wickens, 1997; McCann, Foyle, & Johnston, 1993; Wickens, 1997).

Consistency – Another display principle that applies once a HUD is introduced to the cockpit is that of consistency between the HUD and HDD, especially in the case of primary flight displays. The format of information that is similar in these displays should be consistent, if not identical. To the extent possible, pilots should not be required to translate between head-up and head-down display formats: the transition should be seamless. Otherwise, needless workload is imposed on the pilot along with the possibility of misinterpretation.

Gestalt perception – Applied in the current context, gestalt perception means designing symbology so that significant events or trends are evident, not from examination and interpretation of the individual symbol elements, but from the pattern of these elements or their movement. This allows perception of the event or trend via a global, automatic, preattentive process. As an example, consider an airplane that has just lost power. A pilot should be able to discern this, not through lengthy examination and interpretation of individual HUD symbol elements, but at a glance via the distinct pattern of movement of these elements associated with a loss of power (e.g., airspeed, altitude, and vertical velocity all move counter-clockwise while climb-dive marker, flight-path marker, and acceleration carat all move downward in the HUD field of view). A related concept is that of emergent features (Wickens, 1992), the idea that

displays should be designed so that significant trends, events, or states emerge from underlying individual display elements to be perceived globally and preattentively.

Symmetry – The concept of display symmetry is one example of an emergent feature that is particularly relevant in the current context. Display elements may be designed so that symmetry is achieved when a desired aircraft state is achieved (e.g., pitch and bank steering bars form a symmetric cross when an aircraft is precisely on course and on glide-slope). An example of this in a synthetic vision display is proposed by Theunissen (1997). Head-down tunnel-in-the-sky displays may be designed so that symmetry is achieved relative to the frame of the display. This allows the pilot to determine that the aircraft is in straight and level flight and on course at a glance: if it is, the lines of the tunnel will be parallel to and equidistant from the edges of the display frame. If it's not, this symmetry will be broken.

Implications For Design

How are all of these issues synthesized to create a useful head-up synthetic vision display? We will illustrate by stepping through two design decisions that have led to formats tested at AFRL.

Path format – We start by examining pilot information requirements. Among the things a pilot needs to know about his/her commanded path are:

- Where it is now
- Where it is going
- Where the aircraft is in relation to it
- Where the aircraft will be in relation to it in the future

To meet these information requirements, we could simply draw a perspective view of a line and show a couple of dots for where the aircraft is now and where it will be in the future. This would certainly minimize clutter. However, the commanded path is actually four dimensional: the pilot has an assigned altitude, course, heading and airspeed. Therefore, the path format should show the pilot where these are and where the aircraft is in relation to each of them. These requirements may be met by either the pathway format shown in Figure 1 or the tunnel format shown in Figure 2.

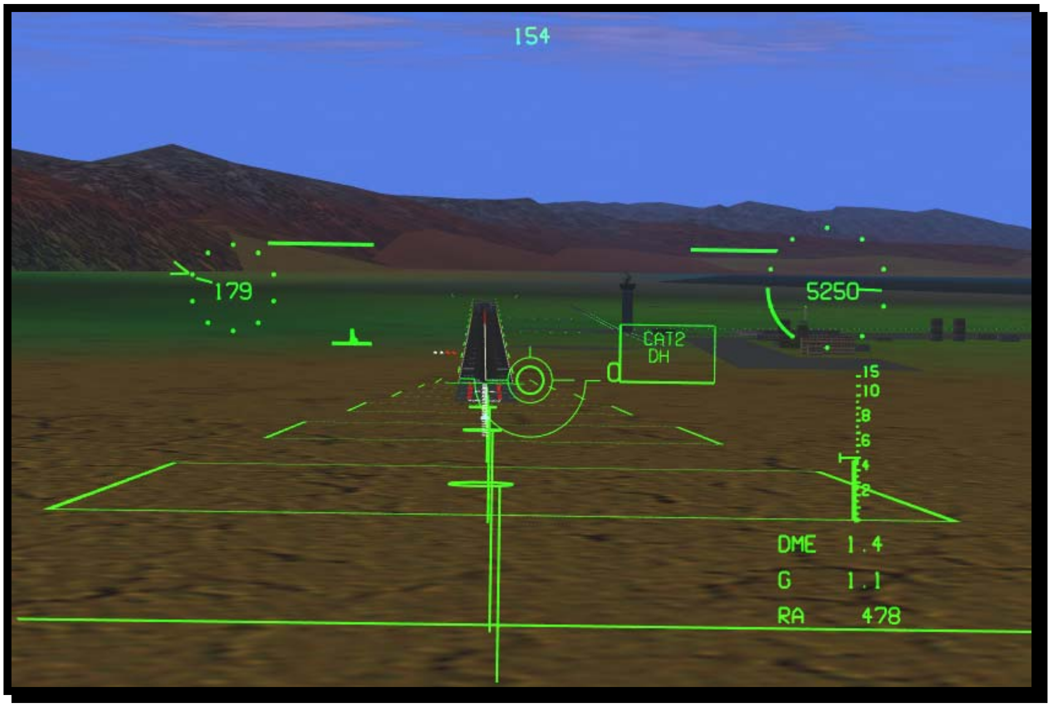

Figure 1. Pathway-in-the-sky synthetic vision format for head-up display.

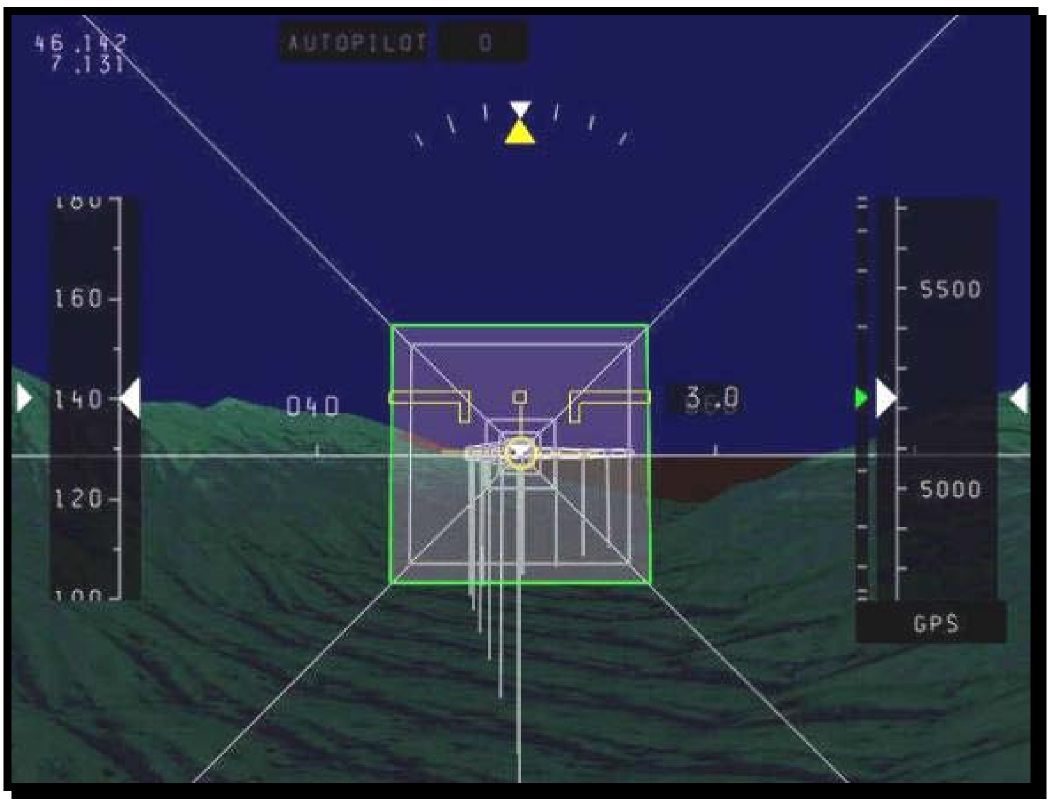

Figure 2. Tunnel-in-the-sky synthetic vision format for head-down display (adapted from Theunissen, 1997).

While the basic information content of these displays is similar, it is interesting to note the disparities between them, especially in the context of the depth and self-motion cues and display principles discussed previously. With regard to the commanded path, both displays contain strong splay, depression angle, motion parallax, and discontinuity rate cues. Both displays include ground intercepts, accurate object interposition, and relative height cues. By incorporating a “follow-me” aircraft of known size, the pathway display incorporates the depth cue of apparent size in what is essentially an indicator of commanded airspeed and altitude. However, unlike the tunnel display, it does not show all dimensions of the pilot’s commanded corridor (assigned altitude block is not overtly displayed) and it does not have the extra discontinuity rate and splay cues provided by the lines making up the sides and top of the tunnel.

What about consistency? The default answer would be that if the designer chooses a pathway head-up, then a pathway should be displayed head-down. Similarly, if the designer chooses a tunnel head-down, then a tunnel should be displayed head-up.

However, we see that the tunnel display involves more clutter than the path display: were the tunnel to be displayed monochrome and head-up, its elements would be less easy to separate perceptually and the pilot would have to peer through a great deal more green to see the view through the window. On the other hand, whether viewed against an HDD frame or a HUD combiner glass frame, the tunnel does provide better emergent features in the form of symmetry and gestalt perception.

Is there a way to realize the advantages of a tunnel without the associated clutter – and achieve consistency between head-up and head-down displays? If one considers that “consistency” does not mean “identity”, the answer is yes. One way of achieving this would be to display a less cluttered version of the tunnel head-up and superimpose this symbology on the head-down display. This allows the pilot to transition between head-up and head-down displays without also having to make a mental transition between display formats. This is especially important in the context of a synthetic vision display because the geometric field of view (i.e., the amount of database displayed) will likely be two to three times wider in the HDD than in the HUD (where it must be the same as the HUD’s physical field of view to remain conformal) and pilots will therefore have an even greater need for consistent display symbology landmarks. A notional example is shown in Figure 3. In this case, the head-up display of the commanded path contains only the symbology elements shown in bright green (i.e., “HUD green”) on the head-down display.

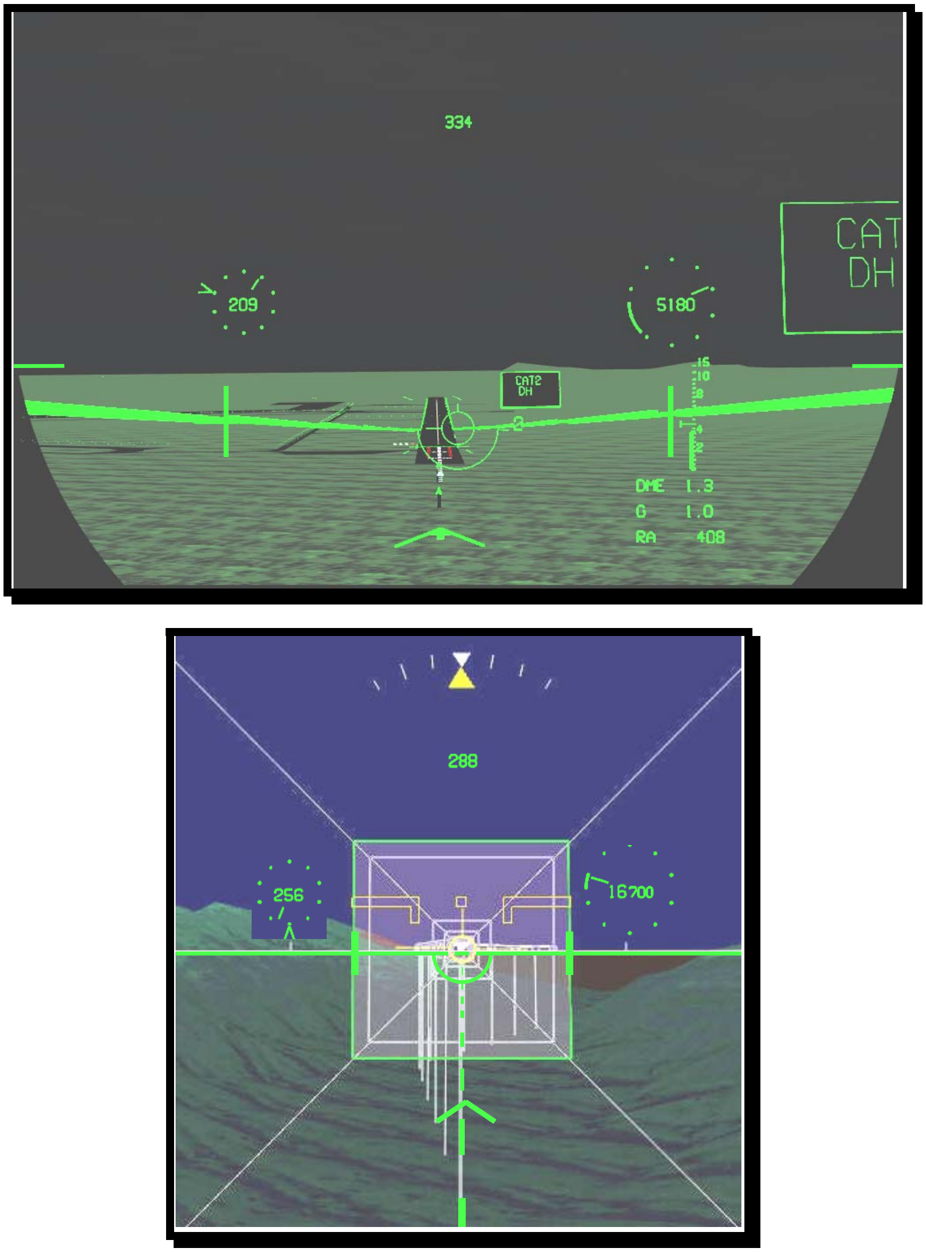

Figure 3. Notional example of how to achieve consistency between head-up and head-down commanded path displays.

Synthetic terrain format – Showing pilots the terrain surrounding the flight path seems like a good way to increase their terrain awareness and prevent CFIT, but what is the best way to do this? Two common approaches (illustrated in Figures 1 and 2) are to superimpose either a texture (sometimes containing photorealistic satellite imagery) or a grid (illustrated in Figure 4) on an on-board digital terrain elevation database.

Again, let's examine these two approaches in the context of the previous discussion of human factors issues. With regard to information requirements, a photorealistic texture seems better suited to the display of landmarks – if there are landmarks to be displayed (a photorealistic texture may not be as useful during low-level flight over water, desert, or other featureless

terrain). For other pilot information requirements, especially the possible need to simultaneously view sensor images and differentiate between sensor imagery and database imagery, a photorealistic texture may actually be counterproductive: it could obscure the sensor image or elements of the photorealistic texture could be confused with elements of the sensor image. A grid, on the other hand, may be superimposed on a sensor image without completely obscuring it. A grid also allows the difference between sensor imagery and database imagery to remain readily apparent.

With regard to depth and self-motion, the only two cues that a photorealistic texture would provide that a grid might not are apparent size (assuming visible landmarks of known size) and texture gradient. It provides much weaker cues to perspective, depression angle, motion parallax, and discontinuity rate than a grid format.

Perhaps the greatest strength of a grid format relative to a texture format is clutter minimization. To the extent that there is a view to be seen out the window, a texture format will obstruct it much more than a grid format will.

Given a decision to portray synthetic terrain as a grid, what should the grid look like? How large should the grid squares be? The default, system-centered answer would be to simply "connect the dots" in the underlying digital terrain elevation database. If the database contains elevation postings every 100 meters, then the grid would contain lines every 100 meters. This approach is shown in Figure 4.

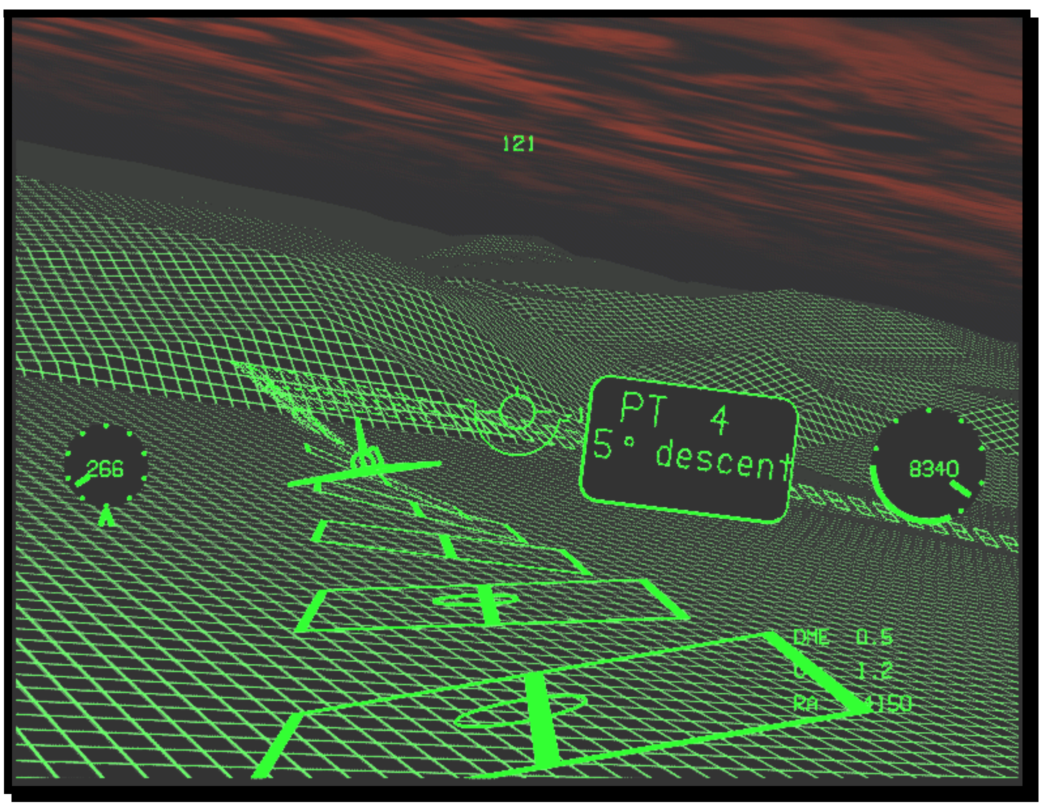

Figure 4. Grid format synthetic terrain with lines every 100 meters.

A better, user-centered approach is to take into account the human factors issues previously described. Three primary considerations in this case are: 1) Pilots' information requirement of

accurately gauging their altitude (or distance) relative to the displayed terrain, 2) Minimizing clutter, and, 3) Maximizing depth and self-motion cues. The second consideration, minimizing clutter, dictates that as few lines as possible constitute the grid. The less clutter associated with the grid, the better the pilot will be able to see either an underlying sensor image or the view through the window. The second consideration, based on existing literature (Dyre, 1997; Flach & Warren, 1993; Flach et al., 1997; Foyle & Kaiser, 1991; Foyle, Kaiser, & Johnson, 1992; Kelly, 1993; Kelly, Flach, Garness, & Warren, 1993), dictates that:

- Splay being a very important cue to perceived altitude, at least two longitudinal lines (lines parallel to the observer's line of sight) should always be visible in the HUD field of view to accurately provide splay cues. Functionally, this means that the grid should be sized so that the center of the HUD field of view spans two full grid squares (or three longitudinal grid lines). This guarantees that at least two longitudinal grid lines will always be available in the HUD field of view to show splay.
- Optical flow, while critical to accurate perception of self-motion (a.k.a., egospeed) and changes in acceleration, serves as visual noise with respect to perception of altitude and is inversely related to accuracy of altitude control. Functionally, this means that grid density should be minimized to reduce the number of elements in the visual flow field.
- Edge discontinuity and depression angle, while important factors in determining egospeed and altitude, will be functions of splay and optical flow rate (respectively) in a square grid and thus, as completely redundant cues, need not be separately factored into the calculation of optimum grid size.
- Because apparent size is only an accurate cue when objects (in this case grid squares) have some known or expected size, grid dimensions should remain constant and not change as a function of altitude.

To calculate the grid size needed to guarantee two full squares in the HUD field of view, one must assume a reference altitude AGL, a lateral HUD field of view, and a maximum downward viewing angle over the aircraft nose and through the HUD. Assume an altitude AGL of 1500 feet (a standard pattern altitude for fighter/attack aircraft and other military jet aircraft), a lateral HUD field of view of 30 degrees (the field of view of the LANTIRN HUD aboard F-16s equipped with the LANTIRN system), and a maximum downward viewing angle of 14 degrees at zero pitch (based on the 14-20 degree downward viewing angle actually found in most current fighter/attack aircraft).

Let a equal the altitude AGL, l equal the lateral field of view of the HUD, and v equal the maximum downward viewing angle over the aircraft nose and through the HUD. We must first calculate the minimum distance to the ground viewable through the HUD (d):

$$d = a(\tan(90 - v)) = 1500(\tan(14)) = 6016 \text{ feet}$$

The total width of the ground viewable through the HUD (w) then becomes:

$$w = d(\tan(l)) = 6016(\tan(30)) = 3224 \text{ feet}$$

Dividing this in half (to guarantee two full grid squares in the HUD field of view) and converting to meters yields a grid size of roughly 500 meters, as shown in Figure 5.

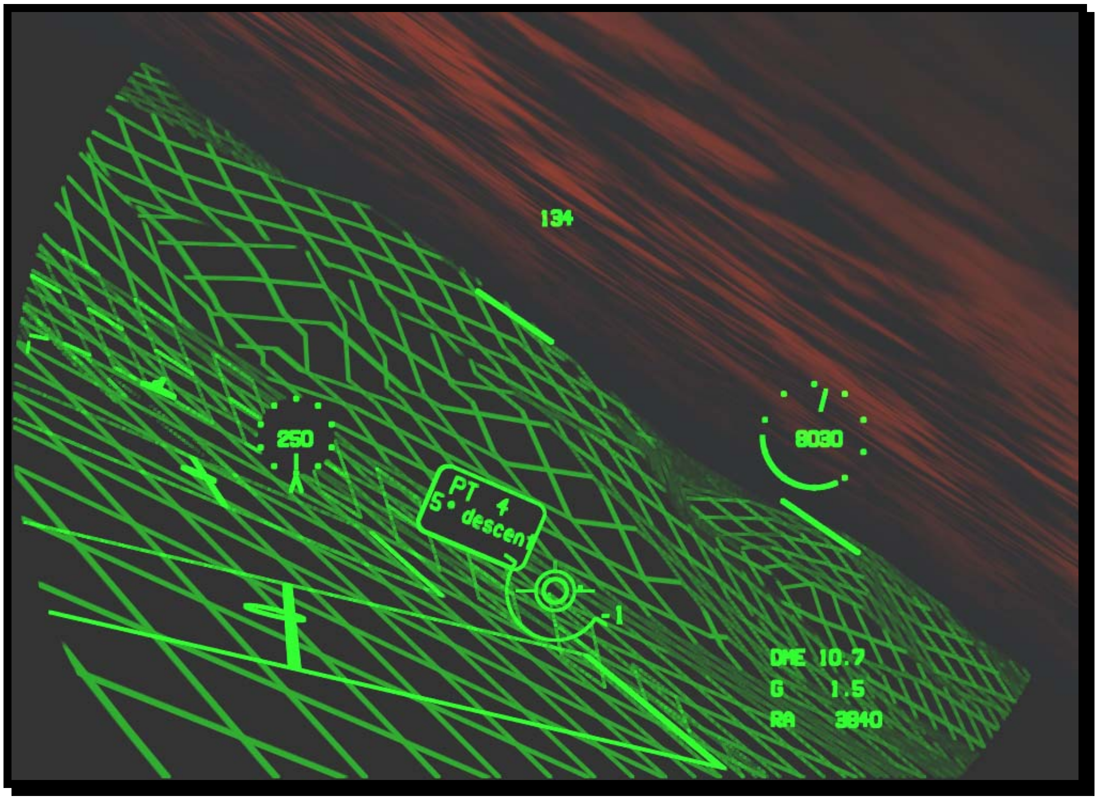

Figure 5. Grid format synthetic terrain with lines every 500 meters.

The above grid size is less cluttered than that in Figure 4, but still contains the same depth and self-motion cues. It should be noted that this example is limited and does not take into account other pilot information requirements such as the density and size of terrain features being overflown. Also, the grid size is optimized only for a fighter/attack aircraft flying at a standard pattern altitude. The parameters of the grid would change as parameters of the HUD, aircraft, and reference altitude change.

RECOMMENDATIONS

- Consider a grid format for synthetic terrain. This maximizes depth and self-motion cues, minimizes clutter, and allows simultaneous view of a sensor image without confusion as to the source of the imagery.
- Regardless of which pathway or tunnel format is chosen (if any), ensure that the only transition required of the pilot as he/she transitions between head-up and head-down displays is eye movement (i.e., ensure a seamless mental transition). One way to achieve consistency between head-up and head-down displays is for the head-up display to show a minimal set of the head-down symbology.
- Where feasible, symbology design should allow pilots to process the display preattentively (i.e., using global or gestalt perception). Emergent features such as symmetry should be used to indicate significant events or aircraft states.

The advent of synthetic vision in the cockpit is imminent. Synthetic vision systems represent a means to solve the problem of controlled flight into terrain, a problem as old as human aviation and one that continues to prove extremely costly in both military and civil aviation. Enabling technologies are all maturing and several substantial efforts are now under way to transition synthetic vision systems from laboratories to cockpits. Care must be taken as these systems are developed and fielded to take into account human factors issues critical to the usability and safety of these displays.

In the next Section, human factors issues related to the display hardware are discussed.

II. DISPLAY REQUIREMENTS FOR SYNTHETIC VISION

The on-going revolution in information availability is not limited to email and web based communications, but is also occurring in increasingly crowded skies. Aircrews will be expected to effectively exploit new and updated information from on- and off-board sources to improve the likelihood of mission success. The capabilities of displays on board aircraft and the information presentation format will affect aircrew ability to manipulate and manage this new wealth of information. As discussed in Section I, one set of systems that will impact the use of displays in the cockpit in the next decade falls under the heading of Synthetic Vision Systems (SVS). Each SVS involves the use of on-board databases that may contain detailed information about flight hazards (e.g., terrain), navigational aids, tactical elements, and flight plan. The information in these databases can then be presented to aircrew to enhance weapon system effectiveness by providing more accurate and current data, increasing crew situation awareness, optimizing workload, and increasing system flexibility. As more information becomes available and storage capacity of on-board systems increases, the pressure to display information in an effective manner rises.

Related to this is the movement to open military aircraft to new off-board data sources, loosely given the name “Real Time Information in the Cockpit (RTIC)”. The RTIC concept assumes a set of enabling technologies: 1) a datalink capability, 2) an accurate geopositioning capability—such as the Global Positioning System (GPS), and its more accurate variant, Differential GPS (DGPS)— 3) a robust and distributed Command, Control, Communications, Computers, & Intelligence (C4I) system, and 4) sufficient display space and capability. Specifically, RTIC proposes to provide timely and reliable information regarding any number of pertinent factors, including, but not limited to: defensive and offensive air-to-air and surface-to-air threats, hostile force locations, mission re-routing, weather updates, information on friendly forces, communications, support, and mission changes. Initial use of new information sources will likely be on head-down displays (HDDs), with eventual incorporation in Head-Up and Head-Mounted displays (HUDs and HMDs, respectively).

One issue raised by the expanded availability of information is the set of modalities used to present it to the aircrew. One option of course, is to simply place a new display and/or computer into the cockpit. As an example, the Airborne Broadcast Intelligence (ABI) system is one such RTIC system that fuses available near real-time intelligence, digital mapping, and imagery information and displays it in the cockpit. In its current state of development, ABI is a “strap-on” computer workstation that utilizes a traditional desktop display employing drop-down menus and “hot button” interfaces. As such, use of the ABI system currently involves an additional dedicated crewmember, responsible for ABI system operation and communication of the relevant information to the flight crew. Because real estate in the cockpit is limited, there are only so many new displays, computers, and crewmembers that can be added. Perhaps a better option is to integrate the on- and off-board data flow into flight system displays and make it available to the entire aircrew. This option places more demands on the displays in the cockpit, some of which are not up to the task. More capable displays will eventually be required to handle the new level of information that aircrews will have and need to perform their missions. The purpose of this section is to describe some of the information and display requirements associated with new technologies expected to reach military cockpits in the next decade.

HEAD-DOWN DISPLAY REQUIREMENTS

With regard to HDDs, the physical characteristics required for a synthetic vision display are not significantly different from those that have become standard in current glass cockpits. Performance requirements driving cockpit display technology include sunlight-readability and/or night vision compatibility—neither of which is present in consumer displays. Hopper has examined performance requirements for defense applications and compared aircraft cockpits to other crewstations. For research purposes, a commercial off-the-shelf (COTS) color active-matrix liquid crystal display (AMLCD), cathode ray tube (CRT), or other display technology defines a baseline for visual display performance. Certified aircraft cockpit display hardware, however, is custom designed and manufactured, albeit commercial fabrication facilities and components are used wherever possible. Night vision filters for backlights, dual backlighting for day/night mode, anti-reflective coatings, electromagnetic interference filters, and dimming electronics are all necessary in military cockpit displays but are simply not included in COTS displays. These additional features degrade the visual performance of the underlying COTS display. This degradation must be factored into efforts to correlate laboratory research to flyable hardware. Efforts to integrate display components designed for consumer products are always underway but typically fail to achieve certification—or worse, deliver performance disappointment to aircrews (degrading combat performance and engendering new development efforts).

The resolution and color capabilities of head-down synthetic vision display formats may, or may not, be especially demanding. Some approaches to synthetic vision simply use color to fill code areas, a common approach being to use similar colors to those found on traditional aeronautical charts (e.g., blue for Class B controlled airspace, purple for Class C controlled airspace). Detailed images equivalent to current print maps and charts in all detail, however, require color pixel densities of over 200 per inch, or twice that in fielded aircraft. Another synthetic vision approach uses photorealistic texture maps based on satellite imagery overlaid on underlying digital terrain elevation data to provide the pilot a display that is as close as possible to what he/she would see out the window in conditions with ceiling and visibility unlimited. This approach is somewhat more demanding of the color rendering capability of the display used. The grayscale of cockpit displays is typically 16 to 256 levels (4 to 8 bits per monochrome pixel); however, human visual capability, real world scenes, and advanced sensors are several orders of magnitude more detailed (14-20 bits per monochrome pixel). The sensors research community has informed the display research community that higher grayscale performance in the cockpit is needed for future systems. Because most operations are purposefully carried out in relatively calm air and most flight time is in level flight, higher resolution displays could improve productivity of aircrews by enabling advanced synthetic vision formats.

The primary challenge in selection of an HDD for synthetic vision is size: the bigger the better. In contrast to a traditional attitude indicator display, the size of a head-down synthetic vision display is directly related to how much of the world is viewable by the pilot. What avionics engineers are often tempted to do, usually in response to complaints of pilots who feel they are "looking at the world through a soda straw", is to independently manipulate the geometric field of view (GFOV) of the display in an attempt to compensate for small display size. With respect to GFOV, synthetic vision systems displaying a database-based image are similar to systems displaying a sensor-based image (whether a single sensor or a fused image from multiple sensors). The field of view (FOV) of a sensor is often greater than the FOV provided by an HDD

when viewed from the cockpit design eyepoint. As an example, suppose the maximum FOV of a Forward-Looking Infrared (FLIR) sensor aboard an aircraft is 25º. The most desirable approach is to include a display in the cockpit that is capable of displaying the entire image on a display that also has a FOV of 25º when viewed from the cockpit design eyepoint. This results in a cockpit display in which the GFOV of the image displayed matches the FOV of the display hardware and the overall image is accurate: neither magnified nor minified. This approach is shown in Figure 6.

Figure 6. Representation of a forward-looking infrared sensor image from a 25° FOV sensor shown in a 25° FOV display.

Unfortunately, the cockpit display in the above example is not one currently found in any military cockpit. It would have to be roughly 15-in. wide to result in a FOV of 25º at a viewing distance of 30".

$$(FOV = 2(\arctan(0.5(\text{display size})/\text{viewing distance}))).$$

Now suppose a more likely scenario in which, because of cost, weight, or space limitations, the largest HDD available to the cockpit designer is a 6" wide multifunction display (MFD). At a design eyepoint of 30", the FOV of the MFD – the angle subtended on the pilot's retina – would be roughly 10º (2(arctan(0.5(6")/30")) = 11.4º). The cockpit designer is now faced with a choice: either the MFD can display less than half the image the sensor is capable of showing, or the MFD can show the entire sensor image. If the designer chooses the former, sensor capability is wasted and pilots will voice the familiar "soda straw" complaint. If the designer chooses the latter, pilots can now see the entire sensor image, but it is minified by a factor of roughly 2.5 to 1. These two approaches are illustrated in Figure 7.

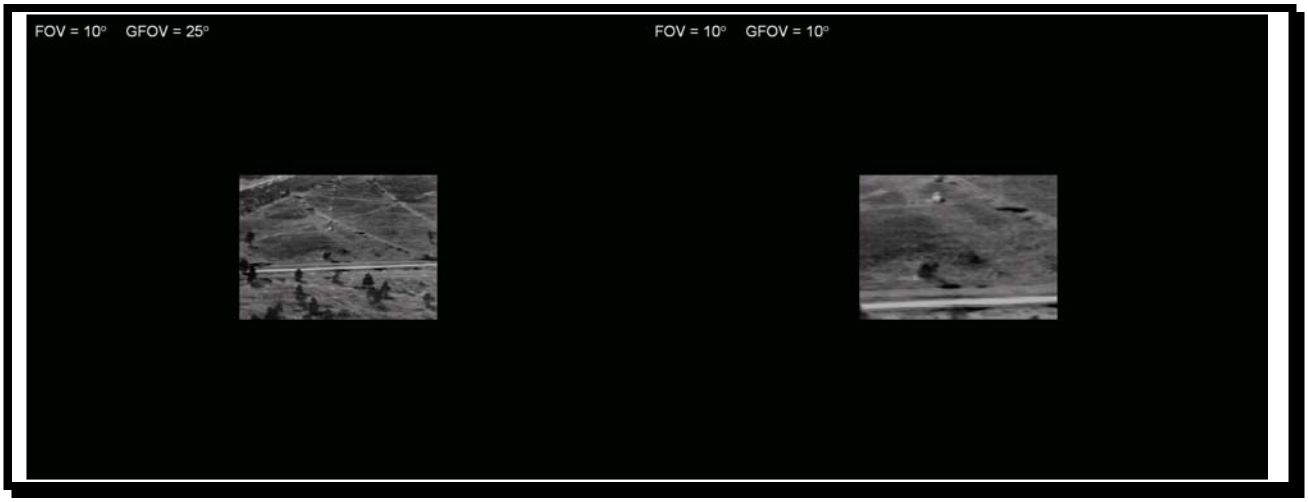

Figure 7. Illustration of two design choices when faced with a mismatch between FOV of sensor or synthetic image and FOV of cockpit display: minify the image and allow the pilot to see all of it (left), or discard part of the image while maintaining accurate scene geometry (right).

Pilots will almost always choose the option associated with a higher GFOV because it allows for greater situation awareness. However, the ramifications of this choice go well beyond situation awareness and consequences can be severe. Choosing a higher GFOV in this case results in minification of the image and perceptual distortions. These distortions, of depth perception and angular perception (especially depression and glide-path angles), can be subtle and not obvious unless the resultant display is compared side by side with a non-minified image. The distortion of perceived size (minification) is associated with distortions in perceived depth (e.g., Bigham, 2000) and has been shown to impact performance and situation awareness. Research has shown that people adapt to these types of images, but adaptation takes time (several minutes) and – most importantly – it is only partial: some distortion of perceived distance and size remains. One can imagine the impact in a high-speed low-level flight environment: simply look at the images presented above and estimate for yourself the size and distance of the lead vehicle in each image and the glide-path angle to the road. It is not the same in both images.

Until and unless truly panoramic HDDs are included in the cockpit, pilots will be forced to adjust to any mismatches between an HDD's physical FOV from the design eyepoint and the GFOV of the image contained in the display. However, the larger the HDD that a cockpit designer has available, the smaller will be any mismatch between the physical FOV of the display and the GFOV of the synthetic image portrayed -- and the less adjustment will be required of the pilot. The primary consideration in selecting an HDD for synthetic vision is maximizing the viewable area of the display (solid angle of image at design eye point).

HEAD-UP DISPLAY REQUIREMENTS

The primary driver for including a HUD or HMD in the cockpit is typically the desire for a pilot's eyes and attention to remain focused outside the cockpit while needed information is shown on the HUD or HMD. From a human factors perspective, two critical factors driving symbology design decisions (including any HUD or HMD synthetic vision symbology) are a pilot's need to see through the display, and the criticality of the information displayed. As a

general rule, the number of pixels in the HUD or HMD should be the absolute minimum needed for the pilot to safely accomplish the mission. Anything more than this minimum is usually perceived as clutter. Further, the information that is displayed should not draw pilots' attention away from the external visual scene. Research has shown that the more conformal a HUD or HMD symbology set is (i.e., the more the symbols in the HUD or HMD conform to objects in the external visual scene or far domain), the better pilots will be able to attend simultaneously to the information contained in the symbology and events in the external visual scene.

In the case of a HUD or HMD synthetic vision display, the GFOV of the synthetic image will be identical to the physical FOV of the display from the design eyepoint. Any mismatch between these two fields of view will produce misregistration between objects in the synthetic image and objects in the external visual scene on which the synthetic image is overlaid. While this may be acceptable in complete instrument meteorological conditions (i.e., when there is absolutely no external visual scene underlying the synthetic imagery), research has shown that misregistration between synthetic and real imagery in conditions allowing a simultaneous view of both has a significant adverse impact on subjective ratings of the usability of the synthetic imagery and pilot acceptance of the resulting display. In the case of a HUD or HMD, the reason to select a display with the largest FOV possible is not to minimize perceptual distortions caused by a GFOV/FOV mismatch, but because an increase in FOV results in a 1-to-1 increase in GFOV – and a 1-to-1 increase in the extent of the synthetic image viewable by the pilot.

Perhaps the primary requirements of a HUD or HMD used as a synthetic vision display are accuracy (temporal and spatial across the entire system), brightness, and the capability to simultaneously display multiple image sources. The display designer may or may not have much direct control over temporal and spatial accuracy. Processing delays in avionics, optical distortion associated with the windscreen or canopy, and exact placement of the pilot's eyes will all lead to spatial and temporal inaccuracies that may produce misregistration between synthetic and real images. However, the display designer should take whatever steps he/she can to ensure that the display optics do not contribute to misregistration and that the pilot (or maintainer) has the capability to "boresight" the system to compensate for static and dynamic sources of error.

Brightness is always important in HUDs and HMDs because they must be readable against extremely bright backgrounds: primary symbology must be legible against a glare source on the order of 10,000 fL. Brightness is also important for any synthetic image underlying this primary symbology. If the maximum brightness achievable by a HUD raster is only 50 fL or so, then the display may be suitable for use only at night. While synthetic vision has been proposed as a technology that is most useful in reduced-visibility conditions, reduced visibility is not always associated with reduced illuminance. One example of this is flight in clouds near the top of a cloud layer. Such an environment could easily wash out a synthetic image if it is not displayed with sufficient luminance. Further, there are some occasions when pilots might find synthetic vision displays useful even in visual meteorological conditions (VMC). For example, mishaps have occurred in VMC on approach to unfamiliar snow-covered airfields, over open water, and over open desert. In such cases, normal depth and self-motion cues are degraded and synthetic vision could be a useful means of regaining situation awareness lost due to lack of these cues – but only if the synthetic image is bright enough to be seen in these conditions. Finally, synthetic vision HUDs and HMDs should be capable of simultaneously displaying two image sources, as in a stroke-on-raster HUD. Most current synthetic vision concepts call for primary flight symbology (i.e., critical gauges and alphanumerics) to be displayed as a separate entity from the

underlying synthetic image. This allows declutter and brightness controls to function independently and also allows the symbology designer to use brightness coding to perceptually separate the content of the two images.

III. SYNTHETIC VISION FORMAT DEVELOPMENT

The National Aeronautics and Space Administration (NASA) Aviation Safety Program (ASP) included the Synthetic Vision Systems (SVS) program, the largest active synthetic vision research and development effort for the aviation environment. Comprised of NASA personnel and industry partners, the SVS team conducted tests aboard the Airborne Research Integrated Experiments System (ARIES) Boeing 757-200 aircraft to study the utility of a system for approach, landing, and ground operations. During trials at Dallas-Ft. Worth (DFW) in October of 2000, NASA and Rockwell Collins tested a generic, opaque texture map format and a photorealistic, opaque texture map format in a Flight Dynamics HUD. All testing occurred at night. In both conditions, pilots had the option to declutter the HUD. At the same time, these formats were also tested on the head-down display (HDD). Additional features examined on the HDD were display size and pilot selectable field-of-view. Results of the DFW trials based on pilot comments showed a pilot preference for photorealistic terrain over the generic format for judging distances and closure rates.

Rockwell Collins, Flight Dynamics, and Delft University are also working together to produce synthetic vision systems for HUDs and HDDs, see figures 8 and 9.

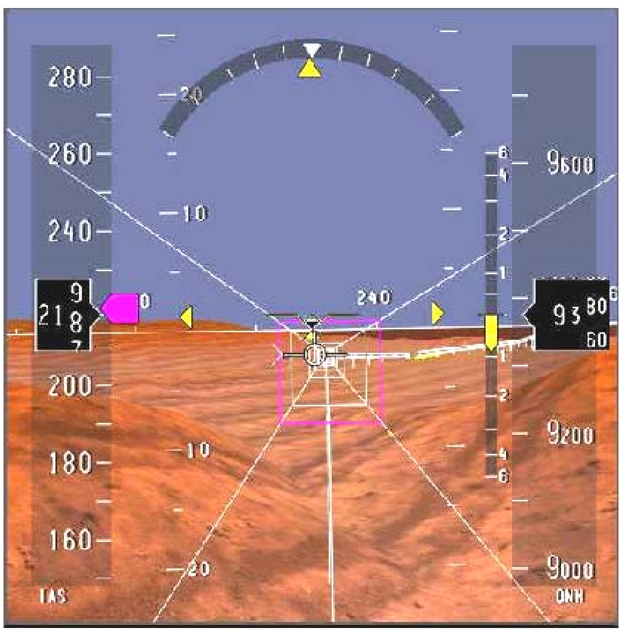

Figure 8. Image of the Head-Down Display symbology and the texture map synthetic terrain being developed by Rockwell Collins.

Figure 9. Image of the Head-Up Display symbology developed by Rockwell Collins.

The goal is to improve pilot awareness of both navigational and terrain features by using a combination of Tunnel-in-the-Sky and database-derived synthetic terrain. Head-down, the synthetic terrain may be dynamically color-coded for the level of threat it represents or displayed as a texture map. Head-up, synthetic terrain may be wire-frame, polygons, or monochrome texture maps and can underlay the basic HUD symbology.
Similar efforts by TU-Darmstadt and Stanford University to display synthetic imagery on head-down and head-mounted displays have yielded the display formats illustrated in Figures 10 and 11.

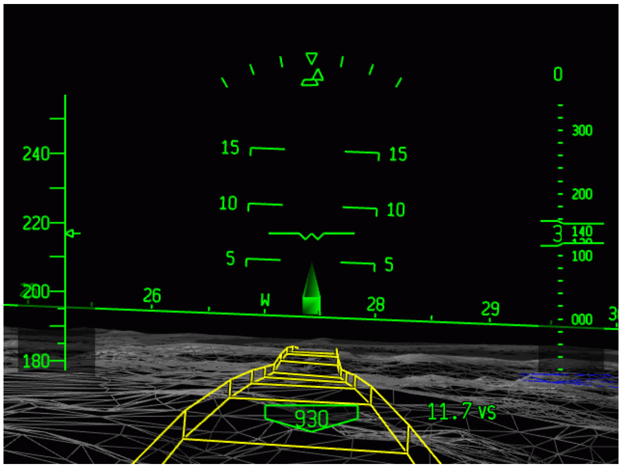

Figure 10. Image of the Head-Down Display symbology and the synthetic vision system being developed by TU-Darmstadt.

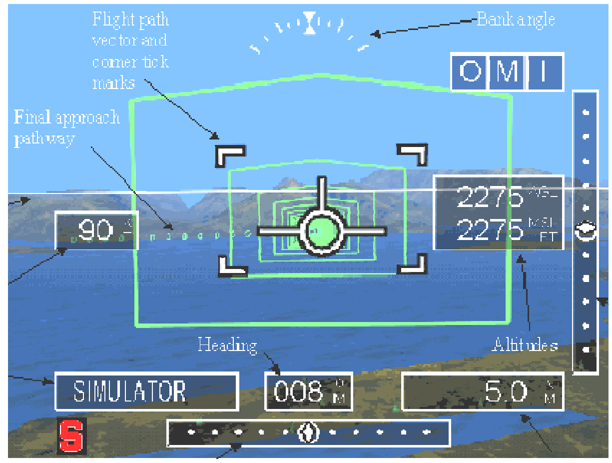

Figure 11. Image of the Head-Down Display symbology and the synthetic vision system being developed by Stanford University.

While civilian efforts have focused on terminal operations, military organizations are also looking at other tasks that require aircraft to be near the ground, such as fixed wing low-level ingress and rotorcraft operations. At AFRL's System Control Interfaces Branch, the research focus has been primarily on HUD pathway symbology for flight guidance, and synthetic terrain imagery for terrain awareness. HUDs are now the primary flight references in almost all fighter/attack aircraft, the Air Force's newer transports, and are being installed as upgrades to some older platforms. Figures 12 and 13 provide examples of the symbology tested under simulated Instrument Meteorological Conditions (IMC) using a monochrome texture map and 100-meter grid, respectively.

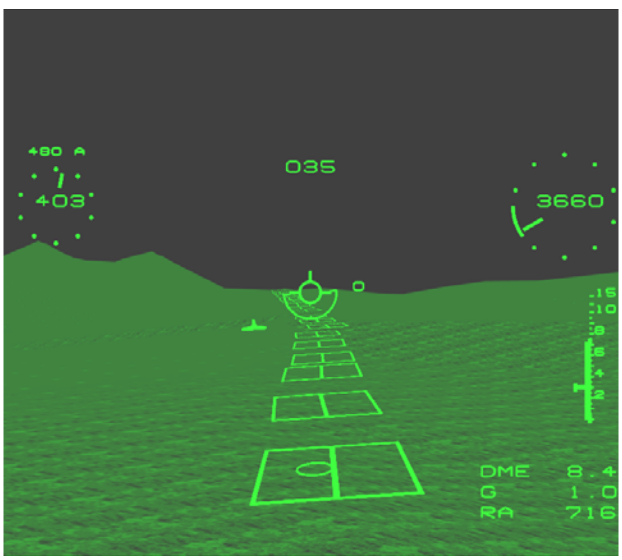

Figure 12. Pathway-in-the-sky superimposed on texture format synthetic terrain.

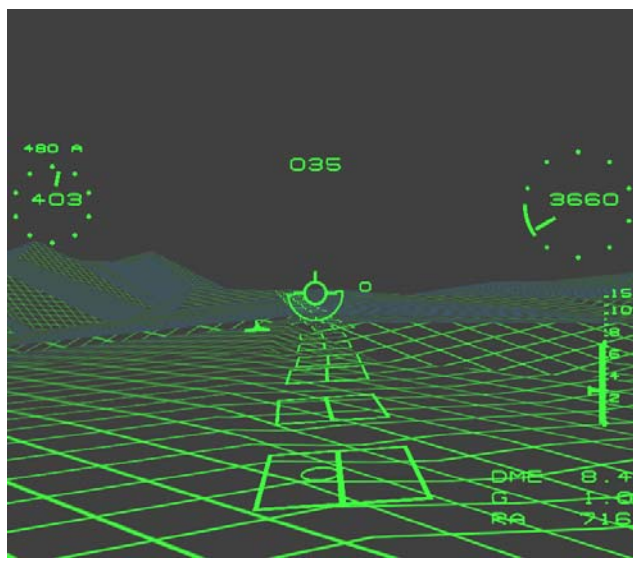

Figure 13. Pathway-in-the-sky superimposed on grid format synthetic terrain.

In the AFRL study, pilots preferred the grid format and reported better situation awareness using this format even though the texture map format is arguably more realistic (Snow & Reising, 1999). Both displays are conformal and the only difference between the two is the format of the

synthetic terrain imagery. The formats above were tested during a low-level ingress task. The grid format will also be tested during approach and landing tasks in an upcoming study.

In related research and under the auspices of the Air Force's Dual Use Science & Technology (DUS&T) program, AFRL and Rockwell Collins conducted simulations and a flight test of head-up symbology for synthetic terrain and pathway guidance in the context of a military transport mission in 2002.

IV. SITUATION AWARENESS

As discussed previously, situation awareness (SA) is a critical factor in the safety and survivability of USAF aircrew. Deficits in SA can have profound and tragic consequences, an example of which is the type of accident known as Controlled Flight Into Terrain (CFIT). From 1987 through 1997, the USAF suffered 190 fatalities and 98 destroyed aircraft due to CFIT mishaps (Moroze & Snow, 1999). A CFIT accident is commonly defined as one in which an otherwise serviceable aircraft, under control of the crew, is flown (unintentionally) into terrain, obstacles or water, with no prior awareness on the part of the crew of the impending collision (Wiener, 1977). While warning systems have reduced the rate of CFIT accidents, this type of solution focuses on a symptom: that collision is impending. To eliminate CFIT, we must also focus on the underlying cause: pilots lose situation awareness concerning the relationship between their flight paths and the surrounding terrain. One method of doing this is to include a display of flight path and surrounding terrain in the pilot's primary flight reference, several examples of which were shown in previous sections. The purpose of this section is to compare two situation awareness metrics used in the present research, provide lessons learned in their implementation, and examine the relationship between SA and performance.

A number of definitions and metrics have been proposed for SA. Among the subjective SA metrics proposed is the Situation Awareness adaptation of the Subjective Workload Dominance technique (SA-SWORD)(Vidulich & Hughes, 1991). This technique uses a paired-comparison form presented shortly after testing to elicit relative rankings of all conditions on SA. Vidulich and Hughes (1991) highlight the importance of defining SA for observers performing the paired comparisons to ensure that comparisons are made on roughly the same underlying basis and results then generalize across observers. The definition given subjects in the present research was based on that of Endsley (1995b) and designed to encompass the three levels of SA that she proposes: "Perception of elements in the environment, comprehension of their meaning, and projection of future status."

The only objective SA measure in widespread use today is the Situation Awareness Global Assessment Technique (SAGAT) proposed and tested by Endsley (1995a). SAGAT is a method in which the simulation or test is briefly halted to ask pilots SA-relevant questions. The accuracy with which pilots answer these questions is then the measure of their SA. Because this technique involves interruption of the task in which SA is measured, there is cause for concern about the possible intrusiveness of the technique. Interrupting an operator's task has the potential to interrupt the operator's working memory, attention state, and mental model of the task. Endsley (1995a), using a relatively global performance measure, reports finding no effect of SAGAT interruptions. The design of the current experiment was set up, in part, to directly gauge the intrusiveness of the interruptions associated with SAGAT use.

With regard to correlation between subjective and objective SA measures, the evidence so far leads to the conclusion that there isn't any (Boag, Neale, & Neal, 1999; Endsley, Selcon, Hardiman, & Croft, 1998). One explanation for this may be that operators essentially "don't know what they don't know." Endsley et al. (1998) have proposed that the dissociation is due to subjective SA measurement being based on confidence in perceived SA and conclude that it therefore, "casts some doubt on the validity of subjective SA measurements as an indication of a person's actual SA," (Endsley et al., 1998 p. 86). However, in the studies conducted by Endsley et al. and Boag et al., the measures compared were the Situational Awareness Rating Technique

(SART)(Taylor, 1990) and SAGAT. SART is a subjective technique in which a score is obtained from a combination of operator ratings of their own understanding of the situation, the demand imposed on them, and the supply available to meet the demand. The underlying construct or definition of SA upon which this technique is based (perceived understanding minus the degree to which task demand exceeds operator capability) seems fundamentally different from the three levels of SA proposed by Endsley. Based on the underlying constructs measured by the two techniques, it does not seem surprising that a correlation between SAGAT and SART has not been found. Should this be interpreted as a difference between objective and subjective SA measures or as a difference between SA measurement techniques that measure fundamentally different aspects of SA? If one were able to compare SAGAT results with a subjective SA measure that is based upon the same theoretical construct of SA used to generate SAGAT questions, would one still find no correlation between objective and subjective SA measures? It is our contention that by having subjects rate SA using SA-SWORD – and basing their ratings on the same definition of SA used to generate SAGAT questions – the current study is perhaps the first to achieve a true “apples-to-apples” comparison of objective and subjective SA measures. This is crucial to assessing the validity of subjective SA measurement and to discovering whether the basis for dissociations between SA measurement techniques found so far has been operators’ inaccurate perception of their SA, or if it has been, instead, differences in the underlying phenomenon being measured.

METHOD

Participants

Twelve pilots participated in this study. Subject pilots were required to have experience in a military, HUD-equipped, fighter/attack aircraft. All were male with military flying experience ranging from 1,300 to 3,775 hours, with an average of 2,634 hours.

Experimental Design

The study used a 2 x 4 x 2 mixed-factors design with two within-subjects factors and one between-subjects factor. The first within-subjects factor was visibility (Day IMC, or Instrument Meteorological Conditions, and Night IMC). The second within-subjects factor was synthetic terrain type (none, grid, partial grid, and texture-map). The between-subjects factor was type of situation awareness measurement (SA-SWORD only or SA-SWORD and SAGAT).

Procedure

Pilots received training in both the classroom and in the cockpit. Classroom training included briefing the subjects on the purpose of the study, describing the different experimental conditions, and explaining the desired response to TEWS alerts: dodging left or right off the path and “into the weeds” (i.e., going as low as they could to get under the radar) as soon as possible. Cockpit training consisted of cockpit familiarization and flying a practice profile to demonstrate the pathway symbology and allow the pilot to become familiar with the aeromodel.

Subjects flew eight different ingress scenarios (all MK-84 deliveries). Each ingress scenario contained two pop-up SAM threats, one located near the beginning of the scenario and one located near the end of the scenario. These pop-up SAM threats were designed to force pilots off the path so that data could be collected in the absence of the pathway. Pilots continued to fly for fifteen seconds after a TEWS alert sounded, after which the simulation was briefly interrupted

and then restarted with the pilot back on the ingress path. Subjects flew a short practice trial in each experimental condition immediately prior to flying the ingress scenario in that condition.

Pilots in the SAGAT plus SA-SWORD condition answered a total of eighteen questions during each ingress scenario, half (selected at random) during an on-path simulation interruption and half after one of the off-path simulation interruptions that followed each SAM alert. Subject to these restrictions, interruptions were placed at random within the ingress scenario. A sample of the eighteen questions asked of each pilot in the SAGAT plus SA-SWORD condition and their associated dependent measures are shown in Table 1.

Presentation of the ingress scenarios and the eight combinations of weather and synthetic terrain were counterbalanced using a standard Latin square. Odd-numbered subjects were assigned to the SA-SWORD only condition, while even-numbered subjects were assigned to the SAGAT and SA-SWORD condition.

Apparatus

This study was conducted in a single-seat, fixed-base fighter cockpit simulator. Head-down displays included a moving map showing a top-down view of the terrain database and a Threat Electronic Warfare System (TEWS) display to alert pilots of lock-on by surface-to-air missiles (SAMs). A 50° horizontal x 40° vertical field of view (FOV) out-the-window scene was projected on a screen in front of the simulator. A 30° horizontal x 20° vertical FOV HUD was simultaneously projected on the out-the-window screen. The cockpit also included a sound system to generate engine noise and auditory events.

RESULTS

Performance

A MANOVA conducted on the three primary flight performance measures (RMS error in airspeed, lateral , and vertical deviation) revealed no statistically significant effect of the type of SA measurement used ($\alpha \leq 0.2$). The observed power ($1 - \beta$) of this test was 0.27. Similarly, no statistically significant effects were found in univariate tests (ANOVAs) for this variable on Gs pulled while off-path ($\alpha \leq 0.2$, $1 - \beta = 0.29$), MK-84 delivery error ($\alpha \leq 0.2$, $1 - \beta = 0.26$), or reaction time to SAM alerts ($\alpha \leq 0.2$, $1 - \beta = 0.26$).

Situation Awareness

In contrast to performance measures, analysis of SA-SWORD data revealed significant main effects for both synthetic terrain format ($F(3, 30) = 26.43$, $p < 0.001$) and visibility ($F(1, 10) = 5.61$, $p < 0.05$). These are illustrated in Figure 14. The only SAGAT question for which a statistically significant effect was found was Question 7 (see Table 1). The effect of synthetic terrain on error in answering this question was significant ($F(3, 15) = 4.13$, $p < 0.05$) as shown in Figure 15.

Table 1. Sample SAGAT questions used in the study.

SAGAT Question	Dependent Measure
1. Estimate your pitch.	Error in degrees
7. What direction, using the hours of a clock, is the nearest terrain in front of you that is above your current altitude?	Error in increments off from correct
10. Estimate how much you are currently above or below your commanded airspeed.	Error in knots
12. From your current position, what is the best escape route to avoid terrain?	Correct / Incorrect
13. Give a detailed description of the terrain at 10 o'clock, halfway to the horizon.	Correct / Incorrect

SAGAT Questions 13-18 essentially asked the same question (describe terrain), but regarding various distances and directions. The number of correct answers to these questions was therefore also analyzed as a separate dependent variable, but no statistically significant ($\alpha \leq 0.05$) effects were found.

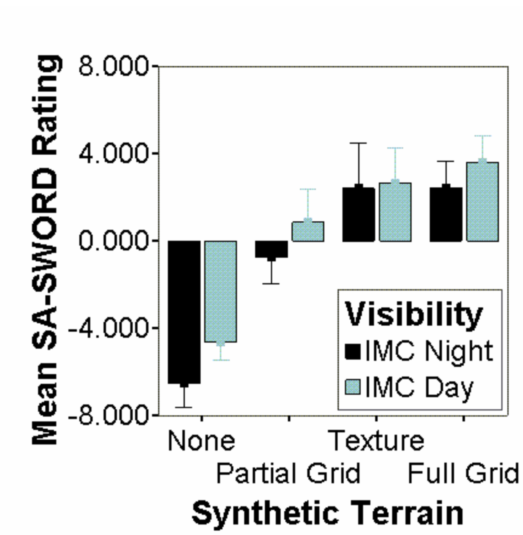

Figure 14. Effect of synthetic terrain format and visibility on SA-SWORD ratings (error bars are 90% confidence intervals).

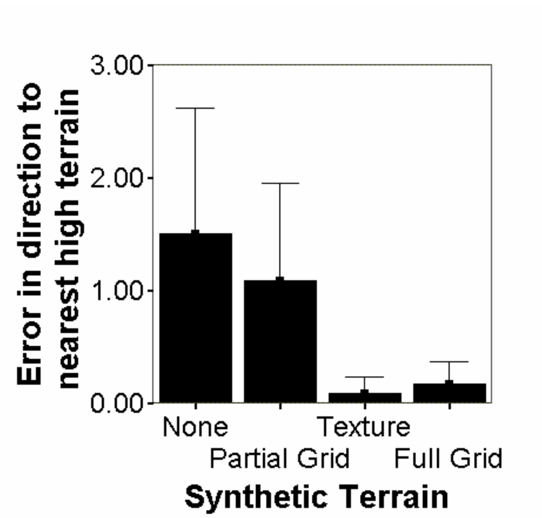

Figure 15. Effect of synthetic terrain format on error in answering SAGAT Question 7 (error bars are 90% confidence intervals).

Concerning the relationship between SA-SWORD ratings and performance in answering SAGAT questions, correlations between SA-SWORD ratings and magnitude of error for SAGAT Questions 1-3, 5, and 7-10 (i.e., those for which numeric error scores were obtained rather than scores of correct/incorrect) were low (absolute values ranging from 0.04 to 0.15) and none were statistically significant ($\alpha \leq 0.05$). Similarly, no significant correlation was found between SA-SWORD rating and number of errors on SAGAT terrain description questions (i.e., Questions 13-18).

With regard to intrusiveness of SAGAT interruptions, the post-session questionnaire asked subjects, “How did you feel about the intrusiveness of stopping the study to ask situation awareness questions?” They were asked to rate intrusiveness on a 1 to 7 scale, with 7 being greatest intrusiveness. Five out of six subjects responded with a rating of 4, or neutral; the fifth responded with a 6.

DISCUSSION

While the results should be interpreted cautiously because of the small sample size (n of 6 in the relevant cells for the between-subjects comparison), they indicate no strong relationship between SA and any of the performance measures used. This was true not just for flight performance measures, but for measures (e.g., reaction time to a SAM alert) that might be expected to be more dependent upon SA. The finding of large differences in SA-SWORD ratings between experimental conditions, without associated performance differences suggests that the relationship between performance and subjectively perceived SA may be especially tenuous. Like those of previous studies (Boag et al., 1999; Endsley et al., 1998), the results of this study lead to the conclusion that there is not a strong relationship between subjective (i.e., SA-SWORD) and objective (i.e., SAGAT) measures of situation awareness – even when the definition and dimensions of SA used as the basis for each technique are identical.

Finally, these results also support the hypothesis that task interruptions associated with SAGAT do not affect performance. In written comments, two pilots indicated specifically that they felt the interruptions did not affect their flying performance. However, pilot comments also indicated that their attentional or cognitive behavior may have been altered by the fact that questions were asked. In the words of one, “As the study went along it became a game to see how many details of the maneuver you could remember.” In the words of another, the questions, “helped force an increase in maintaining a good scan of all the data, knowing I might have to recite specific parameters.”

Lessons Learned

Both SA measurement techniques have advantages and disadvantages. SA-SWORD has global sensitivity, but not the diagnosticity of SAGAT. Also, as has been pointed out previously, operators don’t know what they don’t know and, like most subjective techniques, there is the possibility of halo effects from performance level or other intervening variables. In the current study, we wished to measure SA both on-path and off-path. The SA-SWORD technique is not designed to do this, but SAGAT was readily adaptable to this and is, in general, suitable for measuring SA during different within-scenario conditions, although this can make random timing of SAGAT interruptions more difficult.

While it has good diagnosticity, SAGAT results in multiple variables (the error on each question) rather than a single SA score, and combination of these variables into an overall measure of SA can be problematic. Also, instead of interval-scale data, SAGAT questions often yield correct/incorrect data, lessening the power of statistical analysis techniques that may be applied. Finally, SAGAT is only as good as the questions asked. Good questions require a task analysis, pilot testing to ensure that questions are relevant at each interruption and that subjects respond appropriately, and reliance on subject-matter experts for questions and often for scoring. In our case, correct answers to several of our most interesting SAGAT questions could only be gleaned from screen captures of the scenario after data collection. This was time-consuming and sometimes imprecise. It was our experience that the SAGAT technique is associated with substantially greater overhead than SA-SWORD in terms of simulation preparation, data collection, and data analysis. However, lack of intrusion on performance, the face validity of the technique, and it's usefulness as a diagnostic tool lead us to conclude that it is a valuable technique and one that we will use in the future – in conjunction with a subjective measure of SA.

V. EFFECTS OF PRIMARY FLIGHT SYMBOLOGY ON WORKLOAD AND SITUATION AWARENESS IN A HEAD-UP SYNTHETIC VISION DISPLAY

This section reports the results of a study in which HUD-experienced pilots flew simulated complex precision approaches to landing in three visibility conditions, with and without synthetic terrain, using either pathway-in-the-sky symbology or more traditional military standard HUD symbology. Workload and situation awareness measures were collected to determine the relative workload associated with these conditions and if, as has been proposed elsewhere, flying a pathway-in-the-sky display is associated with "cognitive capture", or a decrease in situation awareness concerning things other than the pathway. It was hypothesized that including pathway and synthetic terrain in a head-up primary flight display would result in a conformal symbology set that naturally draws pilots' attention to external events. It was also hypothesized that workload could be reduced by allowing pilots to maintain spatial orientation via preattentive processes rather than relying on instruments requiring focal vision and active interpretation.

Controlled Flight Into Terrain (CFIT) accidents continue to be a major source of fatalities and airframe losses in both military and civil aviation, despite on-board warning systems (Moroze & Snow, 1999; Scott, 1996). Examination of evidence from the USAF Safety Center reveals that a causal factor in over half of these accidents is related to some deficit in situation awareness (SA) (Moroze & Snow, 1999). Current on-board warning systems (e.g., the Ground Proximity Warning System) have reduced CFIT dramatically, but are designed to prevent disaster once it becomes imminent (i.e., once the system detects that an aircraft flight path will be below some minimum safe altitude). What are needed are systems to improve pilot SA to the point where the need for warnings of imminent disaster are greatly reduced or even eliminated. Both enhanced (sensor-driven) and synthetic (database-driven) vision systems have been proposed as means to enhance pilot SA and reduce accidents caused by SA deficits. Synthetic vision systems have several features that strictly sensor-based systems do not. Among these features are infinite field of regard, field of view limited only by display hardware, range up to (and even beyond) the visible horizon, and ability to portray surrounding terrain regardless of atmospheric conditions. Synthetic vision systems are only as reliable as the database, navigation, and display subsystems upon which they are built, but even with these limitations they seem a useful adjunct to traditional navigation aids and sensor systems. Research in the Air Force Research Laboratory has demonstrated substantial increases in pilot SA with the addition of synthetic terrain to a simulated HUD (head-up display) (Snow & Reising, 1999). Further, this increase in SA was associated with a reduction in ground impacts during the low-level ingress scenarios used in these simulations. An example of the synthetic terrain used in this study is shown in Figure 16. The grid format shown in this figure was associated with the largest increase in SA overall (i.e., in Instrument Meteorological Conditions (IMC) both night and day) and is the format that was used in the current study. This format is also easily distinguishable from sensor imagery and therefore suitable for use in displays combining sensor and database imagery.

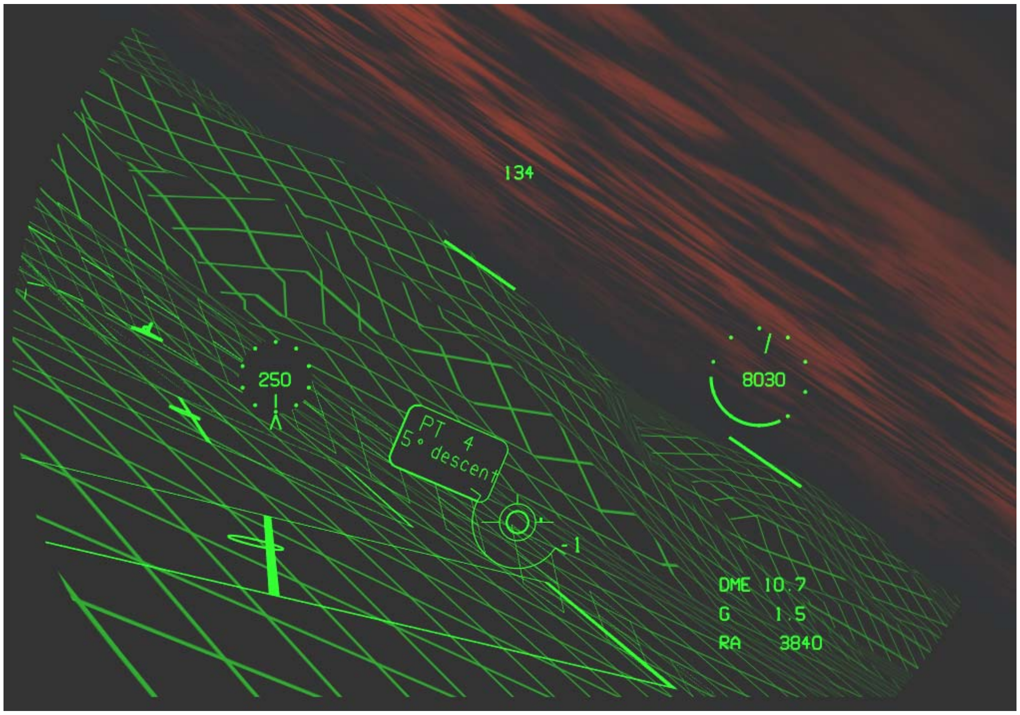

Figure 16. Grid format synthetic terrain.

Previous research in this same laboratory (Reising, et al.,1995) has shown that a pathway-in-the-sky similar to the Command Flight Path Display tested in the 1980s (Hoover, Cronauer, & Shelley, 1985; Dittenhauser, Eulrich, Reynolds, 1983) allows pilots to fly complex precision approaches in IMC at night roughly twice as well compared to the current military standard head-up display (MIL-STD HUD) found in MIL-STD 1787C (DoD, 2000). Pilots using the pathway were able to maintain the commanded path with roughly half the error in airspeed, lateral, and vertical deviation. Such complex approaches, with multiple curves and descent rates, may become common in the next decade as augmentation systems to the current GPS signal, both military and civilian, become operational. Later research showed that the benefit of a pathway HUD in landing these approaches did not vary with visibility in three daylight conditions, but did not directly compare the pathway to the MIL-STD HUD (Reising, et al., 1998). While clear differences have been found between pathway and MIL-STD HUD symbology with regard to performance in flying and landing complex approaches, the differential effects of these two symbology sets on situation awareness and workload have yet to be measured. Measurement of SA and workload is especially important in the current context for two reasons: 1) control/response ratio considerations, and, 2) attention management concerns.

Control/response (C/R) ratio refers to the ratio of control movement needed to achieve a given system or display response (Sanders & McCormick, 1987). A low C/R ratio implies a great deal of display movement with little control movement (i.e., high gain) while a high C/R ratios implies the opposite (i.e., low gain). The C/R ratio for a pathway display is essentially determined by the width of the path displayed. Current GPS approaches call for tolerances as tight as ±0.15 nautical miles or roughly 1,800 feet. However, path dimensions in the literature on this topic vary widely. Theunissen (1997) has tested tunnels of roughly 75, 150, and 300 feet in width, Snow and Reising (1999) used a path width of 400 feet. Williams (2002) used a path width of 600 feet, as did the current study, roughly simulating an approach with a Required

Navigation Performance (RNP) of 0.05 nautical miles. Several studies have shown that path and tunnel displays result in less flight technical error relative to traditional flight displays, but the question becomes, "At what cost?" Is this increased precision associated with higher workload? How tight a tightrope should pilots have to walk? Putting a path or tunnel display in the cockpit is likely to be counterproductive if it means that the pilot is so busy maintaining the path that no time or attention can be spared for anything else. It is critical that flight technical error, situation awareness, and workload be measured in conjunction.

With regard to attention management, there is reason to be concerned about cognitive capture or attentional tunneling: the possibility that a synthetic vision display, especially one including a pathway or tunnel, will be so compelling and contain such a large proportion of the pilot's information requirements that awareness of other displays and events will deteriorate in comparison. Some authors report no difference in situation awareness on-path versus off-path (Snow & Reising, 1999), while others report a decrease in awareness of events and information not contained in the synthetic vision display (Williams, 2002; Olmos & Wickens, 1997). To date, most of these studies have been done with head-down displays and the differences found (or not found) seem to be highly task-dependent (but see Fadden, Ververs, & Wickens, 2001). One purpose of the current study was to see whether using a head-up display for synthetic vision, and presumably focusing pilots' attention head-up rather than head-down would alleviate such concerns.

METHOD

Participants

Thirteen pilots volunteered to participate in the study. All were Air Force pilots with HUD experience. Pilot experience ranged from 1700 hours to 15000 hours with an average of 4819 hours. All pilots were male. Pilots ranged in age from 30 to 53 with an average of 39.

Experimental Design

The study used a 3 x 2 x 2 within-subjects design. However, there were only ten experimental conditions: no trials were run in the VMC Day condition with synthetic terrain.

Independent Variables. The independent variables manipulated in the study were, 1) visibility condition (Visual Meteorological Conditions (VMC) Day, VMC Night, IMC Day), 2) primary flight display (MIL-STD HUD vs. Pathway), and, 3) synthetic terrain (Grid vs. None). The IMC Day condition consisted of ¼-mile visibility with a 100-foot ceiling (equivalent to ILS CAT II). Figures 17 through 19 show the MIL-STD HUD in VMC Day, the Pathway in IMC Day, and the MIL-STD HUD in VMC Night with synthetic terrain, respectively. These figures show each symbology set from the same vantage point (short final) and aircraft state.

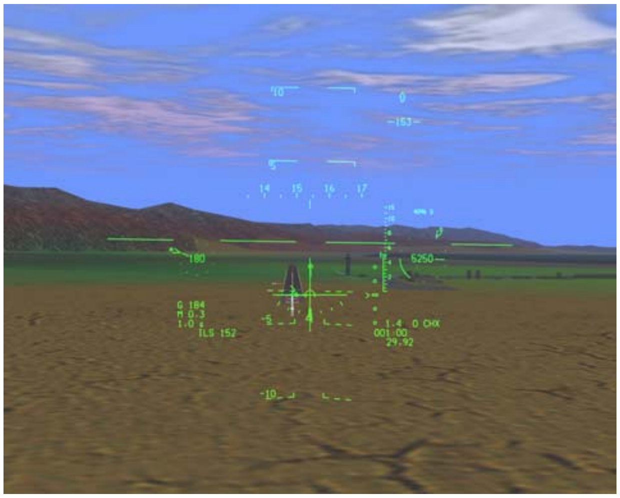

Figure 17. MIL-STD HUD in VMC Day.

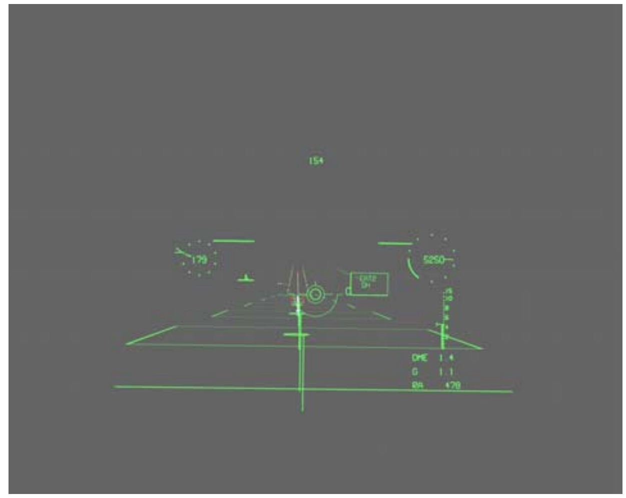

Figure 18. Pathway in IMC Day.

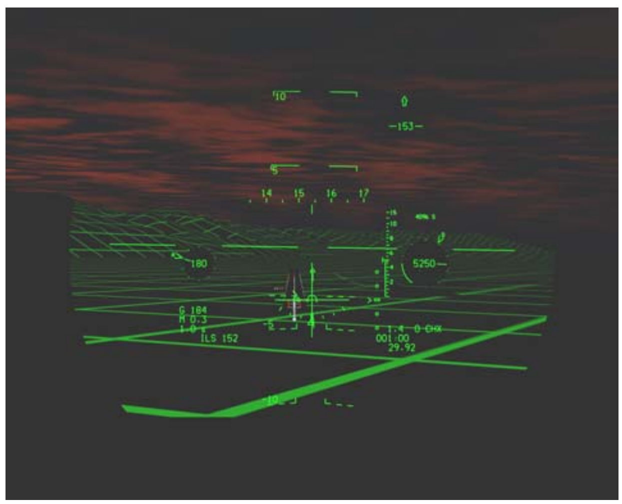

Figure 19. MIL-STD HUD in VMC Night with synthetic terrain.

Dependent Variables. The dependent variables included flight technical error (lateral, vertical, and airspeed deviation) and situation awareness and workload measures. The two situation awareness measures used were the Situation Awareness Global Assessment Technique (SAGAT) and the Situation Awareness adaptation of the Subjective Workload Dominance technique (SA-SWORD). The former is an objective measure based on responses to task-relevant questions (Endsley, 1995) while the latter is a subjective paired-comparison technique (Vidulich, Ward, & Schueren, 1991). The SAGAT questions asked in the study are listed in Table 2.

The two workload measures used were NASA TLX (NASA Task Load Index) and SWORD (Subjective Workload Dominance technique). The former is a rating technique with six subscales while the latter is a paired-comparison technique. Responses to SAGAT questions and NASA TLX ratings were taken during each approach while SWORD and SA-SWORD measures were taken at the conclusion of the experiment.

Table 2. SAGAT questions asked.

1. Estimate your pitch.	14. Does your CDM currently intersect sky, terrain, water, or the runway?
2. Estimate your indicated airspeed.	15. Estimate your drift angle.
3. Estimate your altitude AGL.	16. Are you currently accelerating, decelerating, or neither?
4. Estimate your barometric altitude.	17. Estimate the bearing to the nearest terrain that is above your current altitude.
5. Estimate your current bank angle.	18. Estimate how much you are currently above or below your commanded altitude.
6. Estimate the distance to your destination.	19. Estimate how far left or right you are from the centerline of your commanded path.
7. Estimate the bearing to your destination.	20. What will your commanded altitude be ten seconds from now?
8. Estimate the number of your next waypoint.	21. Estimate the descent angle of your commanded flight path ten seconds from now.
9. Estimate your current heading.	22. Estimate your commanded heading ten seconds from now.
10. Estimate your current descent angle.	23. What direction, if any, will your commanded flight path turn in the next ten seconds (left, right, or none)?
11. Estimate your vertical velocity.	24. Locate all traffic, ground and air, currently present in the environment.
12. The terrain at 12 o'clock, midway to the horizon is: rising, descending, roughly flat, or water?	25. Estimate distance to the nearest traffic.
13. The terrain at 12 o'clock, at the horizon is: rising, descending, roughly flat, or water?	26. Estimate the bearing to the nearest traffic.

Procedure

Participants received an introductory brief, simulator and symbology familiarization, and then flew ten practice approaches, once in each experimental condition. Data collection then proceeded with participants flying ten different approaches twice each (a total of twenty approaches during the data collection phase). Each experimental condition was replicated twice in random order. The simulation was briefly interrupted once at a random interval during each approach to ask SAGAT questions and take NASA TLX ratings. Two to four F-16s were present in the airport environment during each approach with the final (twentieth) approach differing from the rest in that one of the F-16s was stationed on the runway at the touchdown point. This last approach was always conducted in one of the two VMC conditions. Upon completion of all

approaches, participants rated their workload and situation awareness using the SWORD and SA-SWORD techniques, and filled out a questionnaire to solicit subjective opinions concerning the conditions and symbology sets flown.

Apparatus

The cockpit used was a fixed-based simulation of a generic fighter/attack aircraft using an F-16 aeromodel. Primary control inputs consisted of throttle, force stick, touch screen, and gear handle. The out-the-window scene was viewed on three projectors surrounding the cockpit with a total lateral field of view of 110º and a vertical field of view of 30º. HUD symbology was superimposed on the center projection screen with a field of view of 30º lateral by 20º vertical. A picture of the simulator is shown in Figure 20. Head-down instruments included a moving map and a traditional primary flight display (Attitude Director Indicator, Horizontal Situation Indicator, Airspeed and Altitude Indicators). Participants were given an instrument approach procedure to be studied prior to each approach, which they then placed on a kneeboard for reference throughout the approach. A sample approach procedure is shown in Figure 21.

Figure 20. Cockpit simulator used in the study.

RESULTS

Flight Technical Error (FTE)

Flight Technical Error data collected were the airspeed, lateral, and vertical deviations from commanded values. These data were then broken into two groups based on occurrence of a secondary task: non-distracter and distracter. Root Mean Square Error (RMSE) was calculated for statistical analysis. Also calculated from the raw FTE data were the percentages of time spent outside the commanded corridor vertically and laterally.

All of the non-distracter FTE means were significantly lower ($\alpha = .05$) for the pathway condition. Figure 22 shows the means for lateral deviation RMSE and is representative of the other FTE measures (error bars in all figures represent 90% confidence intervals).

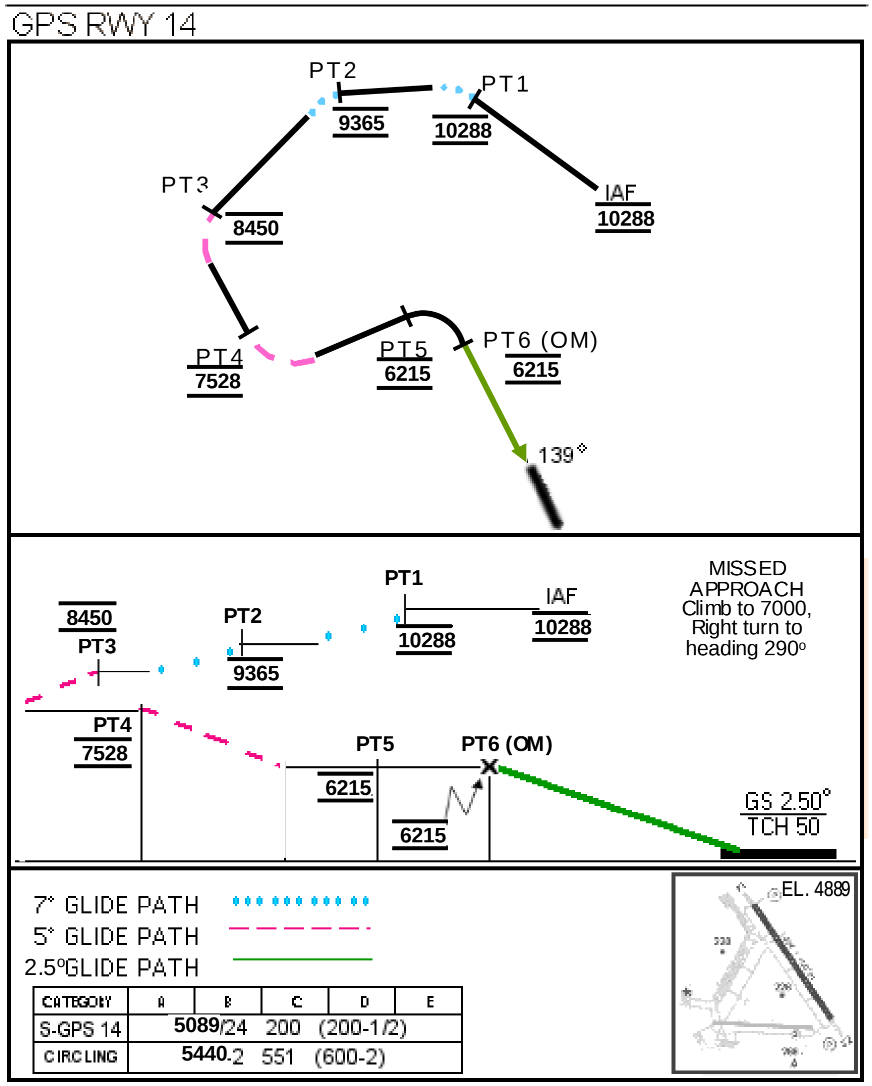

Figure 21. Sample instrument approach procedure used in the study.

Percent time spent off path was also significantly lower in the Pathway condition. For the main effect of the visibility variable, only mean differences in rmse for airspeed (VMC Day vs. IMC Day) and percentage of time off-path vertically (VMC Day vs. VMC Night) were significantly lower (in the VMC Day and VMC Night conditions, respectively).

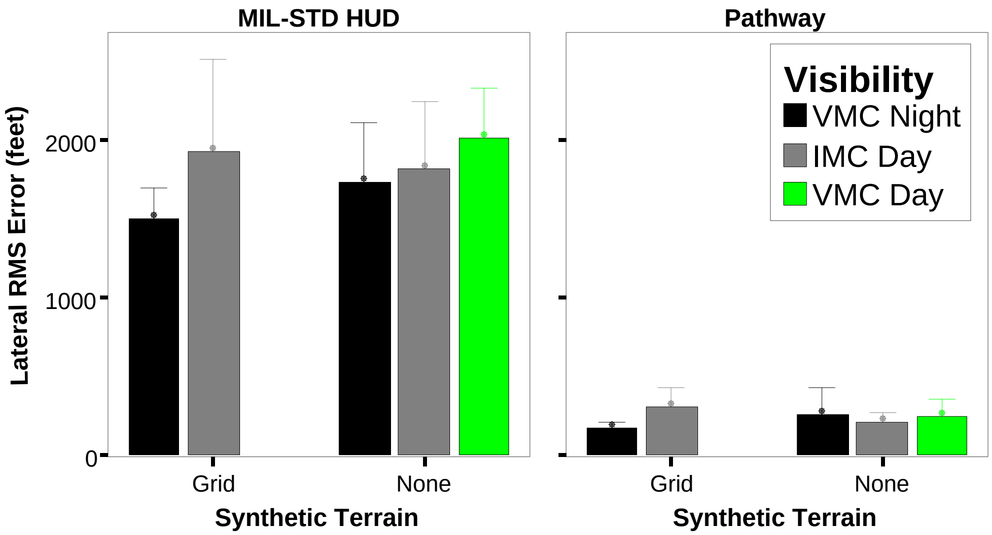

Figure 22. Effects of primary flight display, visibility, and synthetic terrain on Lateral RMSE.

For the distracter data, all of the FTE means were also significantly lower in the Pathway condition (see Figure 23 for a representative graph).

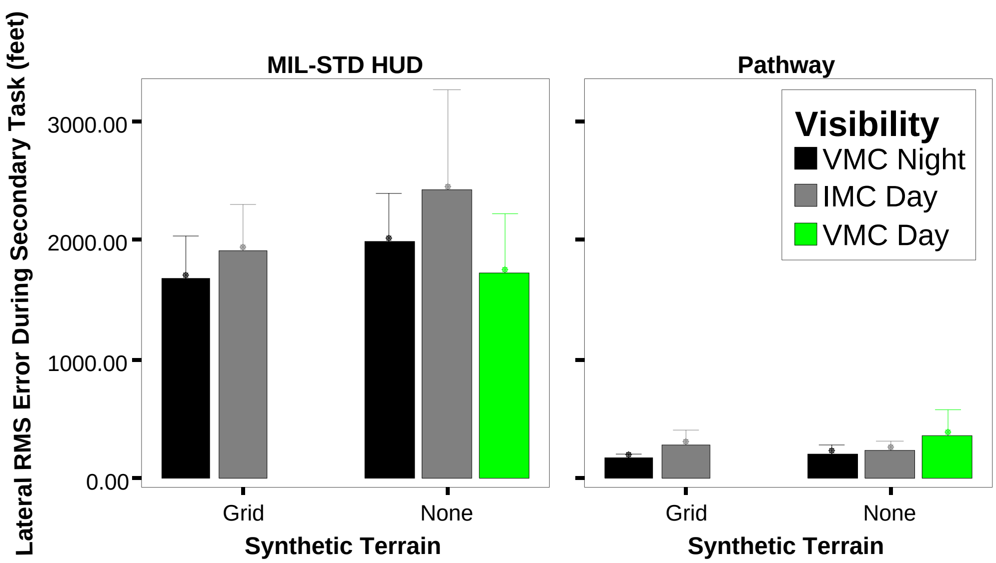

Figure 23. Effects of primary flight display, visibility, and synthetic terrain on Lateral RMSE during a secondary task.

For the visibility variable, no main effects were significant. However, for the PFD * Visibility interaction, a significant difference was found for rmse vertical deviation. This difference occurred for both VMC Night and IMC Day vs. VMC Day. In both cases, the rmse vertical deviation mean was lower for VMC Day in the Mil-Std. condition and higher for VMC Day in the Pathway condition.

The performance of a secondary task resulted in significant differences in the means of absolute lateral deviation, airspeed RMSE, and all measures of percent time off path. Further, the interaction of PFD * Secondary Task also had a significant effect on lateral RMSE and all percent off path measures. Effects on total percent time off path are shown in Figure 24.

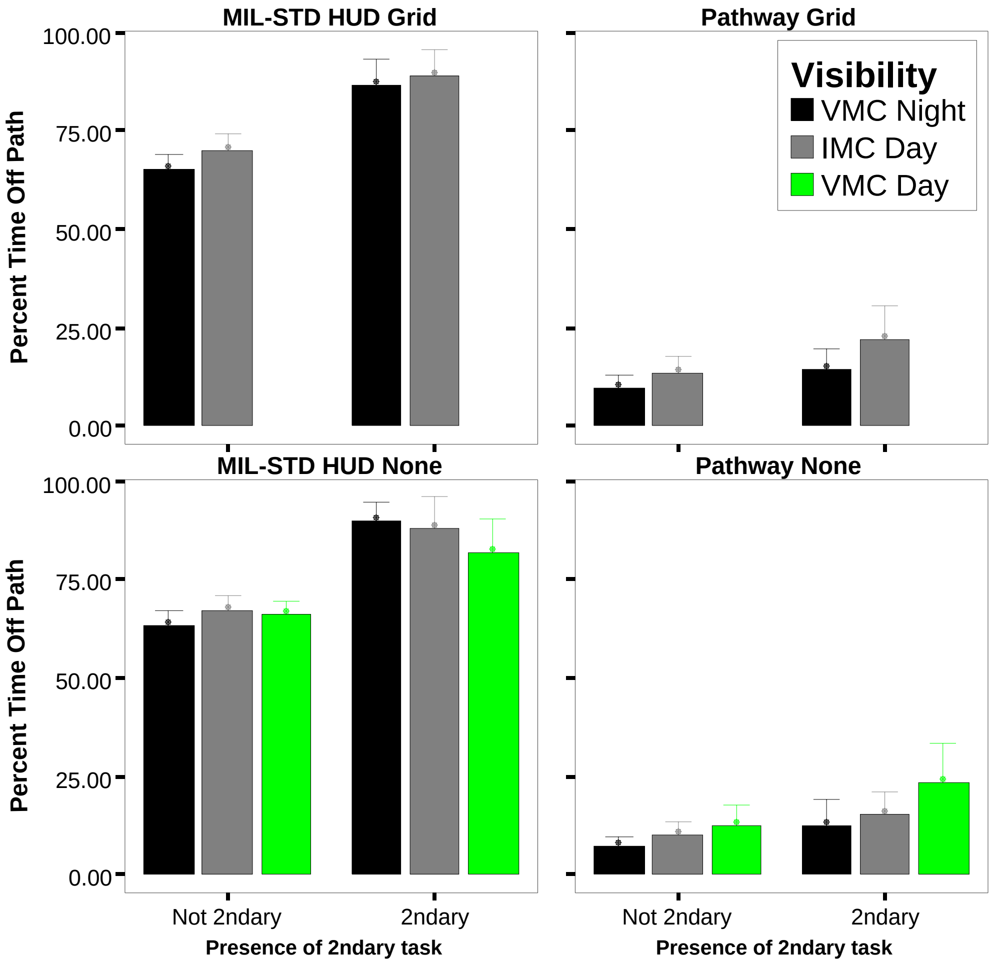

Figure 24. Effects of primary flight display, visibility, secondary task, and synthetic terrain on percent of time off path.

Synthetic terrain had no significant effect on any of the flight performance dependent variables.

A secondary analysis was conducted on the FTEs by adding Secondary Task to the model. Unsurprisingly, results of this model reveal main effects for PFD and Secondary Task. Absolute lateral deviation, RMS airspeed deviation, and percent time offpath (total, lateral, and vertical) were all significant for Secondary Task. Interestingly, the PFD*Secondary Task interaction was significant. Upon further examination, the means for absolute and RMS lateral deviation and percent time offpath (total, lateral, and vertical) were significantly lower for pathway (see Figure 25 for a representative graph).

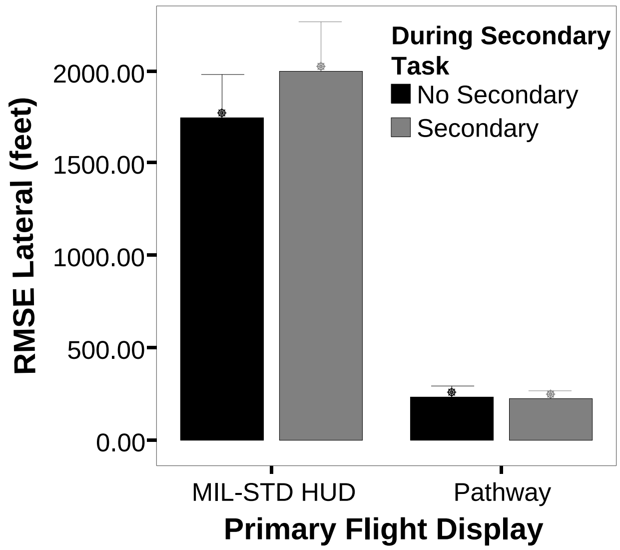

Figure 25. Effects of primary flight display, visibility, and synthetic terrain on Lateral RMSE during a secondary task.

Workload

A repeated measures multivariate analysis of variance was conducted for SWORD and NASA TLX weighted workload levels. Differences were significant for both measures for both primary flight display and visibility, with the lower means (less workload) occurring in pathway conditions. For visibility, significantly lower SWORD means occurred under VMC Day conditions vs. VMC Night and IMC Day. The significantly lower TLX means only occurred under VMC Day when contrasted with IMC Day.

Synthetic terrain had a significant effect on the SWORD variable only, with workload rated lower when synthetic terrain was present. There was also a significant effect on SWORD ratings of the interaction between primary flight display and synthetic terrain, with synthetic terrain rated as reducing workload only in the MIL-STD HUD condition (see Figure 26). Corresponding NASA TLX data are depicted in Figure 27 (use same legend).

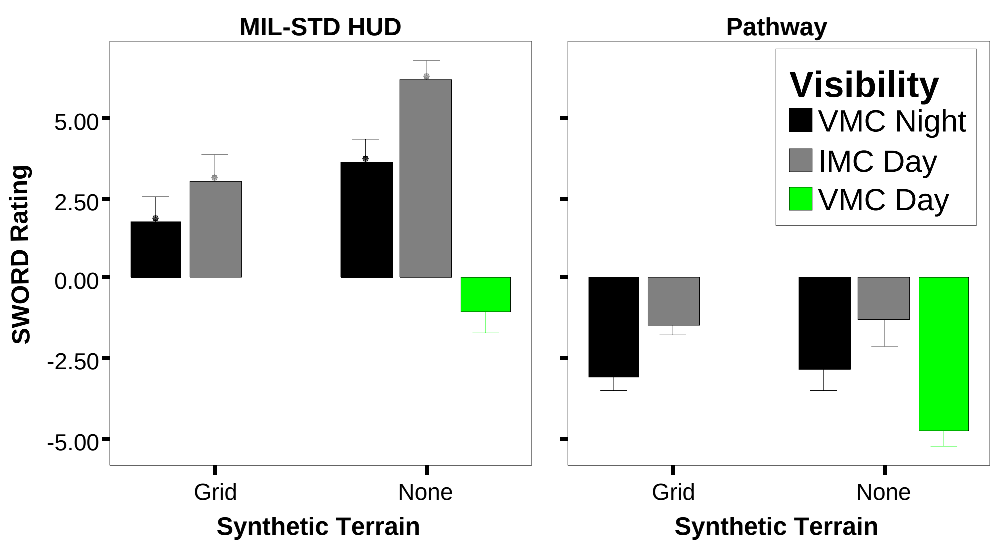

Figure 26. Effects of primary flight display, visibility, and synthetic terrain on SWORD ratings.

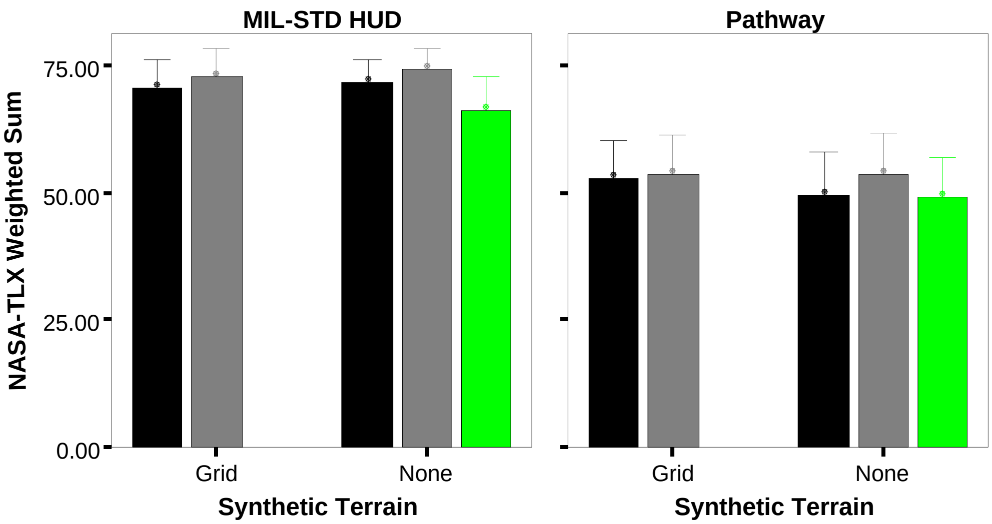

Figure 27. Effects of primary flight display, visibility, and synthetic terrain on NASA TLX ratings.

Situation Awareness

Included in the MANOVA above was the SA-SWORD variable. For situation awareness, the only main effects significant were primary flight display and visibility. The SA-SWORD scores had higher (more SA) means in pathway and VMC Day conditions. A significant interaction was found between primary flight display and synthetic terrain, similar to that found for SWORD data. Effects of independent variables on SA-SWORD are shown in Figure 28.

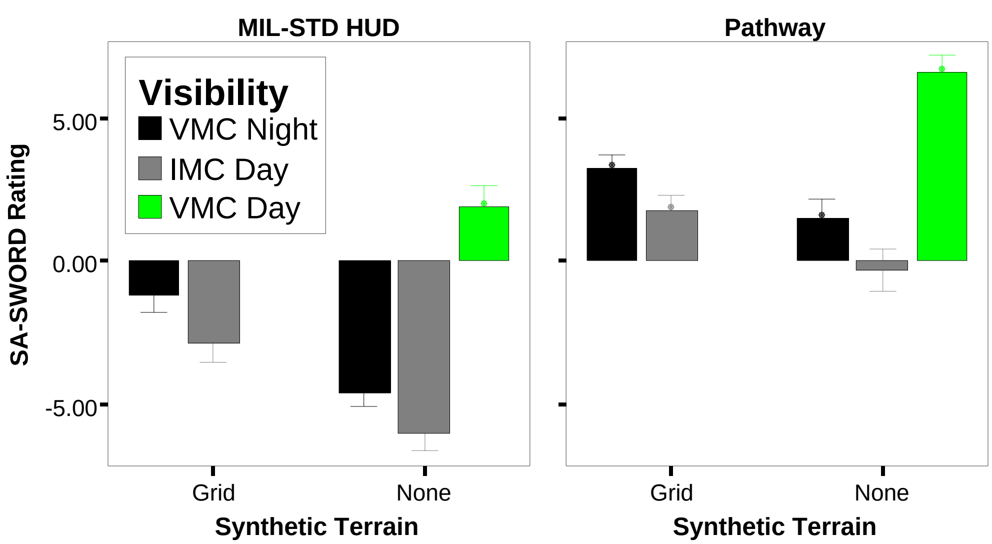

Figure 28. Effects of primary flight display, visibility, and synthetic terrain on SA-SWORD ratings.

The only significant effect on SAGAT scores was the effect of visibility on overall SAGAT score. A test of within-subject contrasts showed that this effect was due to a difference between VMC Day and the other two visibility conditions. SAGAT scores throughout the study were low (pilots typically answered between a third and half of the questions correctly) and it is difficult to

know whether the lack of significant findings for SAGAT scores was due to low statistical power (typical observed power was 0.2), a floor effect, insensitivity of the measure, true invariance of SA as independent variables were manipulated, or some combination of these. Even when groups of related questions were analyzed together (e.g., terrain questions), results were still not significant, although trends were in expected directions. For example, of responses received to SAGAT terrain questions across all pilots, 57 were correct when synthetic terrain was present, versus 40 correct when it was not. Similarly, pilots answered 31 of these questions correctly in the VMC Day condition, but only 17 correct responses were received in the IMC Day condition without synthetic terrain.

Two other results of note were not analyzed statistically: incidence of CFIT, and response to runway incursion. Of the 260 approaches flown during the data collection phase of the study (i.e., excluding practice), seven resulted in controlled flight into terrain. All of these occurred in the IMC Day condition without synthetic terrain. Six of the seven occurred when the pilot was using the MIL-STD HUD.

Software/simulation problems invalidated two of the runway incursion approaches (wingtip and tail lights on the simulated F-16 failed to operate). Of the remaining eleven runway incursion approaches, a correct response to the runway incursion (initiation of a missed approach) was observed on eight of these. In the three approaches in which a missed approach was not observed, pilots executed a normal landing on or very near the simulated F-16 at the touchdown point. Post-experiment questioning revealed that these pilots were totally unaware of the simulated runway incursion. All of the runway incursion approaches in which a missed approach was not initiated occurred in the VMC Night condition, using the MIL-STD HUD, without synthetic terrain.

DISCUSSION

With respect to flight technical error, the results of this study replicate those of previous comparisons between traditional flight directors and pathway displays. Pilots are much better at maintaining the commanded flight path, including airspeed, when using a pathway-in-the-sky display. Indeed, pilots spent roughly four times as much time outside the commanded corridor when flying the MIL-STD HUD as they did when flying the Pathway. The absolute magnitude of these effects is very likely driven by what was, in retrospect, an extraordinarily challenging task: time spent learning the symbology sets, simulator flight control characteristics, and studying approach plates was much less than what one would expect of an operational environment. Further, the paths flown represented something of a “worst case” in terms of corridor dimensions and were designed to test the limits of pilot ability in a precision navigation environment unhindered by the interception and tracking of radio navigation aids. While not a focus of the study, the results support the current strategy of allowing pilots to fly a stabilized approach in IMC (one in which requirements for control inputs are minimized). Several pilots commented on the difficulty imposed by the variety and number of changes in descent angle in the approaches flown.

Despite the demanding task, pilots were able to successfully fly the approaches when using the pathway, even in solid IMC and even in the presence of distracter tasks. The workload and SA data provide insight into why this was the case. Better flight performance in the pathway condition was achieved – not at the expense of increased workload – but because use of the

pathway reduced workload. Indeed, pilots commented that increased situation awareness regarding the upcoming path (and associated control inputs) allowed them to better manage secondary tasks. This is evident in the effects on flight performance of the interaction between primary flight display and secondary task: performance with the MIL-STD HUD worsened significantly more with addition of a secondary task than did performance with the pathway. The NASA-TLX data show that workload decreased roughly 20% with use of the pathway, a decrease that may be practically significant. Experience with this metric indicates that a “redline”, a point at which performance begins to significantly deteriorate, may be around 50 (e.g., Aretz, Johannsen, & Ober, 1995). In the current study, pilots rated their workload near this value when using the pathway, but well beyond it when using the MIL-STD HUD.

While the results with respect to primary flight display are not unexpected, the results with respect to synthetic terrain do contain some surprises. Synthetic terrain appeared to have no effect on flight performance and affected only, 1) the most sensitive measures of workload and SA (SWORD and SA-SWORD), and, 2) only in the MIL-STD HUD condition. As described previously, analyses of SAGAT results were problematic, but these data did trend toward an increase in terrain SA with the inclusion of synthetic terrain. While caution should be exercised in basing any conclusions on only seven events, the fact that no CFITs occurred when synthetic terrain was present seems promising.

The subjective questionnaire asked pilots to rate the usefulness of the MIL-STD HUD, the pathway, and synthetic terrain on a scale from -3 to +3, with -3 being “Extremely Low” and +3 being “Extremely High”. The average ratings were –1.2, 2.4, and 1.2, respectively. A majority of pilots commented that the synthetic terrain would be most useful in IMC or at night. Five of the thirteen commented that they would want control of the brightness or contrast for the synthetic terrain (to include decluttering it entirely), especially on short final. Several of the pilots would have decluttered the follow-me aircraft if they had had the option, and there were several suggestions for adding reference markers (e.g., airspeed, altitude, and heading “bugs”) to the pathway display to support awareness of basic approach parameters, especially in the event of display failure.

While pilots’ ratings of pathway utility were quite high, two of the thirteen made comments that indicated a concern relative to non-pathway SA:

Pilot A: “Very useful in helping the pilot predict where the flight path of the aircraft would be relative to current ownship attitude and heading. However, SA on actual path segment headings or commanded altitudes was not high. Could get complacent "following the path", leading to pilots not maintaining overall orientation to the approach.”

Pilot B: “The pathway format reduced my workload greatly once I acquired a better understanding of the system. Easy to interpret the displayed information. The danger I see here is a pilot can very easily tune out the world around him while totally focusing on the pathway.”

While these comments would support a hypothesis of cognitive capture (or attentional tunneling) associated with the pathway, they are somewhat belied by the runway incursion results: none of the incorrect responses to the runway incursion occurred in the pathway condition. Rather, the results support an alternate hypothesis that – even for an unexpected event – the conformal nature of pathway HUD symbology (especially in combination with a synthetic runway outline) and its head-up location facilitate SA, at least relative to events in the far domain near to or

overlaid by the symbology (Fadden, Ververs, & Wickens, 2001; Martin-Emerson & Wickens, 1997).

Conclusions

As applied research comes closer to actual application, care must be taken in overgeneralizing results. Among things to bear in mind in interpreting the results of this study and related studies that have been published in recent years is that pilots were flying a part-task simulation. Pilot performance, workload, and SA are greatly influenced by several factors common in actual aviation environments that are not common in part-task simulations. Important among these are communications with air traffic management, the presence of other crewmembers, and physical stresses (e.g., G, cold/heat, turbulence).

However, with respect to flight technical error, the results of this study replicate those of previous comparisons between traditional flight directors and pathway displays both in simulation and in flight (Theunissen, 1997; Fadden, Ververs, & Wickens, 2001). In comparison to standard 2D flight directors, pilots are much better at maintaining a commanded path when using a pathway display and it seems likely that this effect is magnified with increasing path complexity. When commanded corridor dimensions (and associated C/R ratios) are held constant, workload is reduced by use of a pathway display and situation awareness is increased. The increase in awareness of future path-related events, especially those associated with control inputs, reduces pilot workload and allows better management of secondary tasks.

The current study certainly does not rule out the phenomenon of cognitive capture or attentional tunneling associated with pathway displays. However, it does support a hypothesis that any such detriment can be alleviated via the placement of conformal symbology in a head-up location. Extrapolating, concerns about decreased awareness of air traffic associated with pathway usage should not be addressed by using symbology other than a pathway, but by including conformal overlays for traffic in the HUD. In pursuing this strategy, research is needed concerning trade-offs between conformal overlays and amount of clutter. Given all the potentially useful database-based information that could be displayed to a pilot (e.g., terrain, traffic, flight path, atmospheric phenomena, airspace boundaries), there is the potential to render a HUD informationally opaque and not useful for its original intended purpose.

VI. MISSION FACTORS IMPACTING SYNTHETIC VISION AND FUTURE COCKPIT CONCEPTS

CREW TASKS AND AIRCRAFT MISSION

Specific tasks or missions require different synthetic vision formats. Just like the civil world, the military owns different types of aircraft to perform different types of missions. The C-17 can perform tactical airlift, the F-16 and F/A-18 provide air interdiction, close air support, and offensive/defensive counterair, while the E-3 Airborne Warning and Control System (AWACS) manages the command and control aspects for other joint platforms in-theater. Such wide-ranging missions require different platforms and subsystems, and synthetic vision systems are among these.

The E-3, whose mission it is to fly high enough to maintain command authority over a certain region of airspace only comes near the ground during takeoff and landing operations. Synthetic vision systems requirements for this type of mission are similar to those of the civil world, including takeoff/landing in fog. Precise geopositioning capabilities through GPS/DGPS technology are necessary for terminal operations, but little else.

On the other hand, an aircraft engaged in close air support in an area of varied terrain may be flying near the ground with very little preplanning due to the dynamic nature of engaging camouflaged and concealed enemy ground forces. Complicating this task even further is the possible proximity of friendly ground forces, increasing the risk of fratricide. Throw instrument meteorological conditions into the mix and the pilot’s task grows more and more difficult. A synthetic view of the local area could conceivably improve a pilot’s awareness of surrounding terrain to that near the level of a clear and sunny day. Indeed, synthetic vision systems have the potential to provide more and better depth and self-motion cues than are normally available to a pilot on such a clear and sunny day. Additionally, because the imagery can be at least partly database driven, the database could contain symbology for ground forces, both friendly and enemy, to improve lethality and reduce the probability of friendly fire casualties, assuming accurate intelligence can be fed into the database in near real time. The capability to update the onboard database through a datalink with offboard sources (such as the AWACS, Joint Surveillance Target Attack Radar System (JSTARS), and Forward Air Controller (FAC), etc.) after arriving in the Area of Operations increases the chance of a successful mission.

LASER THREAT PROTECTION AND NIGHT/WEATHER VISION

Another consideration for the use of SVS is the increasing use of battlefield directed energy such as lasers. Possible enemy use of lasers to blind friendly forces is leading to the development of laser eye protection measures, at this point in time consisting primarily of static vision filters for the common wavelengths of lasers in use. Of course, the use of a filter for a visible laser is going to obstruct the vision of the pilot to some degree. Depending on where the filter is placed, either included in the canopy or special glasses on the pilot, the use of an SVS could compensate for the frequency-specific “notches” in the pilot’s vision by supplementing the real out the window scene. Unless some non-vision-obscuring method for protecting aircrew from blinding energy is discovered, the view “out the window” may become more and more occluded and SVS may be called upon to make up the difference.

The direct view now acquired by the pilot's unaided eyes looking out of current cockpits might be denied even during a clear weather day by directed energy threats. Rules of engagement,

however, require human-in-the-loop to the last moment possible before munitions release and during fly-out to ground targets to minimize collateral damage and civilian casualties. In addition, combat pilots suffer from information overload resulting in loss of situational awareness at times when it is most important: beyond visual range objects are difficult to envision and fit into a total picture; sensor advancements provide ever higher resolution targeting imagery real time in the cockpit. These threats, together with night, in-weather, low-level flight conditions are giving rise to large head-down panoramic displays in 21st century cockpits and make the case for exploration of immersive displays.

As lasers become more ubiquitous, the future military pilot—and even civilian—might have to fly some flight segments without looking out of the cockpit. The canopy would be closed by curtains or by an electrically controlled opaquing layer—only during these times. Then a synthetically generated view of the real world would be created. The control and display system might logically evolve as an extension of present day night/in-weather instrumented flight systems. A more extensive in-cockpit display suite may become necessary to survival and mission success. Such a system might include a 4000 cm^2 (600 in^2) head-down color MFD that would be viewable in sunlight or starlight, plus a helmet-mounted cueing system. The opaqued canopy might include a closable display viewable just in dim ambient to provide simulated vision over the full field of view denied episodically by external conditions. Ideally these displays would be physically redundant yet appear seamless.

PANORAMIC COCKPIT CONCEPT

A program of studies conducted by the Air Force Research Laboratory in 1990 demonstrated an effective way to begin to deal with the threat and synthetic vision issues just described. The approach in this program, entitled "Panoramic Cockpit Control and Display System (PCCADS)," was to provide the pilot with large area displays and a helmet-mounted off-axis target-acquisition weapon-targeting system. There were two projects, one focused near term, one far term (Hopper, 1992).

The PCCADS 2000 cockpit was designed to be realizable with 1995 technology with production by 2000 and featured a 25 cm (10 in.) square tactical situation display and two 15 cm (6 in.) square secondary multifunction displays on either side. All displays were full color capable with a total area of 1110 cm^2 (172 in^2). The test mission was for an F-15E. A 28% increase in exchange ratio was achieved versus the standard F-15E cockpit. An 18% increase was observed for the addition of helmet cueing to the F-15E baseline cockpit. Coupling this large display with a helmet-mounted cueing system (HMCS) for off axis target acquisition resulted in a 45% increase. The F-22A Raptor will realize the PCCADS 2000 concept in a production cockpit (video wall comprising six separate flat panel AMLCDs with having an aggregate resolution of 1.35 megapixels at 5-bit grayscale (32 gray levels) per color in 1290 cm^2 (201 in^2) plus Joint Helmet Mounted Cueing System (JHMCS) add-on. Beyond the PCCADS 2000 cockpit was full PCCADS with a continuous display surface of 200-300 in^2.

SUPER PANORAMIC COCKPIT (SPC) CONCEPT

Hopper (2000b, 2000c) introduced a super-panoramic cockpit (SPC) concept to advance discussion of features that might be explored to implement synthetic vision in both open and closed cockpits. The SPC concept is illustrated in Figure 11. The SPC concept has a central large area display à la PCCADS surrounded left and right by similarly large, curved cockpit-conformable displays with the goal of creating a HDD system with over 100º FOV. The 100º

FOV is an important metric for significantly greater engagement of the capabilities of the human vision system. The HUD is supplemented by a set of deployable flat panel displays to create a second 100º FOV in the direction of forward view; this system affords night/in-weather/in-laser flying capability upon demand. In addition , the SPC concept includes a closable curtain inside of the canopy in the near term that gives way to a flexible canopy display system (CDS) in the far term. Deployment of both the HUD panoramic FPD HUD system and the CDS would be mechanized and typically actuated only upon pilot command. The deployable FPDs and CDS may initially be build using current display technology. In the far term the FPDs and CDS may become roll-up flexible displays based on technology now being created by the Flexible Display Program at the Defense Advanced Research Projects Agency.

Beyond the SPC concept is the immersive cockpit, which provides a maximum possible, 4π steradian, FOV at the resolution of the natural world. For 2-D hardware this system would require some 1 billion pixels to provide for just 20/20 visual acuity.

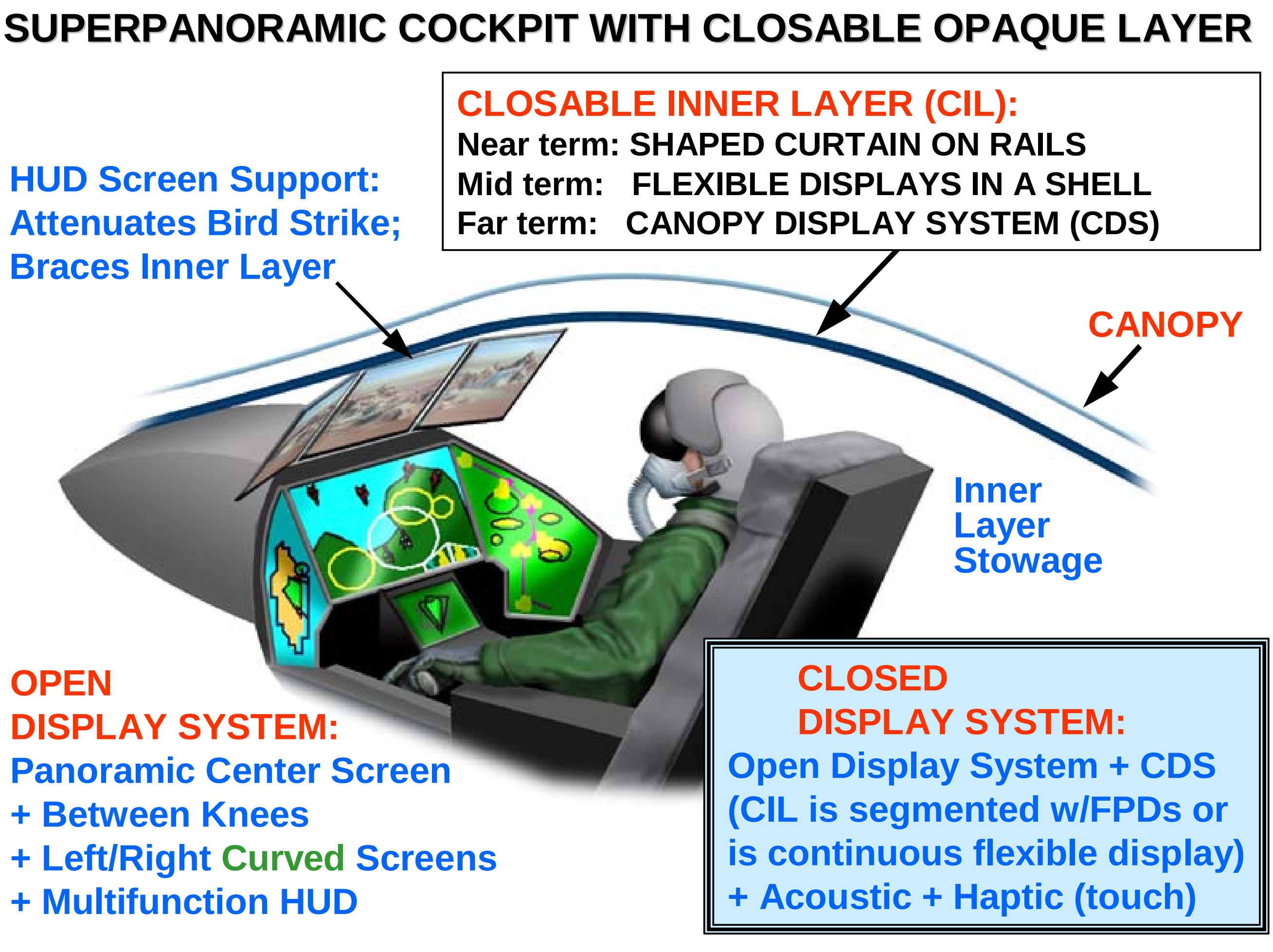

Figure 29. Super panoramic cockpit with deployable flat panel forward vision system and flexible canopy display system.

DISCUSSION

Fielded military cockpits have crossed the megapixel threshold (F-22A, AWACS/JSTARS crewstation). The human visual system is capable of digesting one gigapixel, color high grayscale full motion video in 2D and even more if 3D is considered. A substantial closing of this human vs. fielded gap will make new systems affordable by reducing both crew sizes and training/rehearsal flights while increasing individual effectiveness. A corollary will be to provide the means to operate more effectively during attack mission segments in which direct vision though a canopy is denied by night, weather, or anti-personnel directed energy. Advances in display technology and the advent of digital television will enable a 100-fold growth in cockpit resolution by 2010. Simulators and trainer systems might leverage this technology trend to produce tactical fighter aerospace canopy vision systems at 20-20 resolution (170 megapixel versus present 16 megapixel). Such 20-20 simulators could save jet fuel by reducing training flights, increase effectiveness of pre-mission rehearsal, and enable realistic human factors research on directed energy threats. Uninhabited combat vehicles (UCV) may require addition of inset displays to present high resolution sensors: video (FLIR, LLLTV at 25 megapixel per frame) and stills (4 megapixel satellite photographs and significant portions of 8-30 gigapixel battlefield terrain databases). Work on advanced simulators and UCVs, as well as C4I data walls and complete audio-visual environments (CAVEs), prepare the way for in-aircraft in-spacecraft hectomegapixel display systems with 200 megapixels (160 immersive canopy, 35 panoramic head-down, 5 see-through head-mounted). The hardware technology is being developed to creation of panoramic and immersive cockpit display systems to implement synthetic vision.

We note that the largest display in the F-22A cockpit is just 7.8 x 7.8 in. compared to the 15 x 15 in. minimum size one would need to present imagery from current sensors to the pilot without distortion or cropping. And even the F-22A is not yet fielded. Thus, the display size needs to grow to support both the full use of current sensors as well as the advanced sensors which already have demonstrated even larger fields of view and resolutions over 25 megapixels per frame. Cockpit retrofits as well as new systems programs are envisioned for implementation.

Rules of engagement and technology limits (transmission bandwidth, speed) argue for the retention of a pilot in aerospace craft, albeit with an immersive display capability activated for attack mission segments, in many air and space combat platforms.

An igloo made of eight 25 megapixel AMLCD flat panel displays may be a near term incarnation of the hectomegapixel cockpit display. In the far term, flexible displays on large thin substrates (steel, plastic), produced with printing technology, may permit the design of a closable inner cockpit shell with 160 megapixels on the inside and a deflecting/absorbing layer on the outside.

Eventually, the aggregate resolution of an immersive cockpit might need to be 250 megapixels, a visual photon information flow to the pilot of 360 gigabits per second.

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